Measurement Of Direct Photon Higher Order Azimuthal Anisotropy In $\sqrt{s_{NN}}$=200GeV Au+Au Collisions at RHIC-PHENIX

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Pre-defense Session

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Outline

✓ **Introduction**
- Direct photon
- Motivation

✓ **Analysis**
- PHENIX detector
- Analysis method

✓ **Results and Discussion**
- Neutral pion v_n
- Direct photon v_n
- The probability of resolving photon puzzle

✓ **Summary**

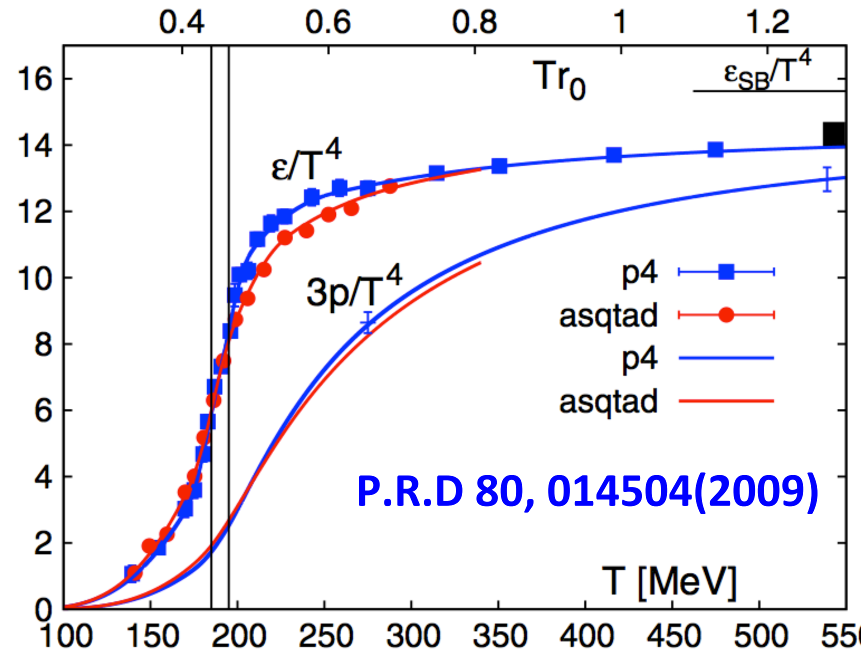
Introduction

Quark-Gluon Plasma at heavy ion collision

Quarks and gluons are predicted to move freely in the state of extremely high temperature and dense matter.

QGP has been created at high energy heavy ion collision.

- RHIC at BNL
- LHC at CERN

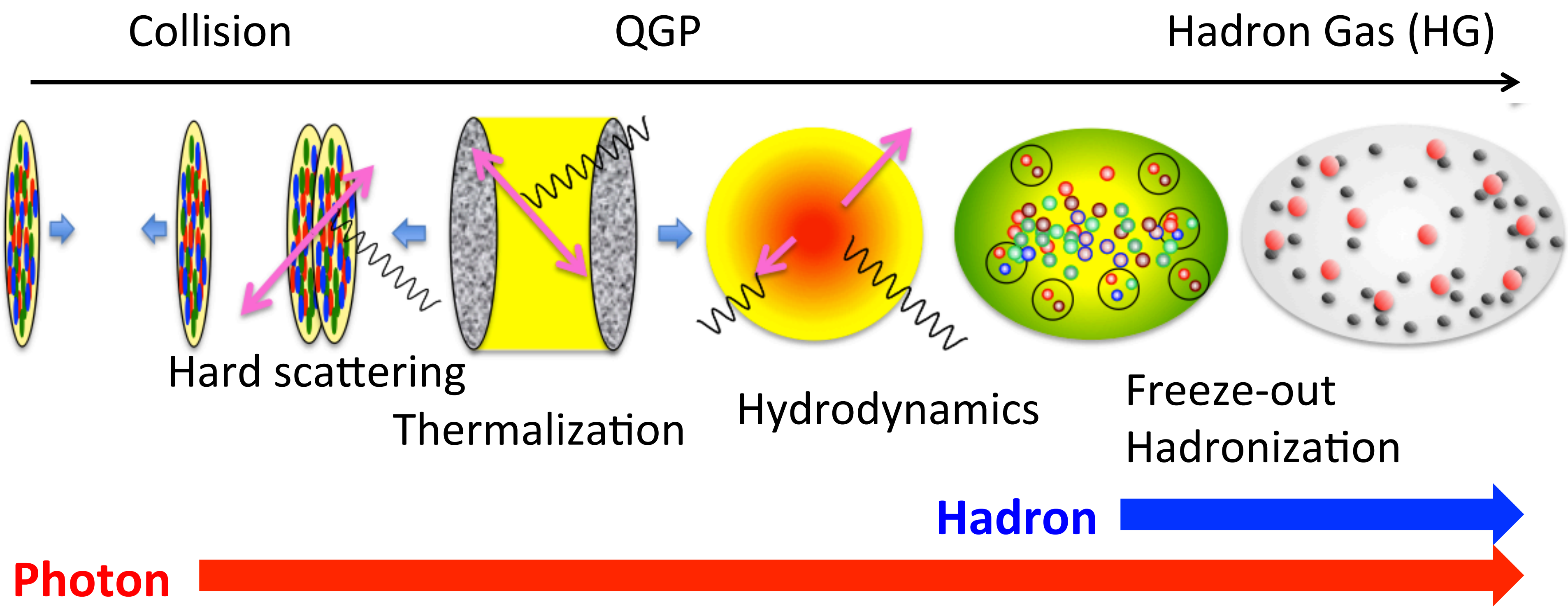


Lattice-QCD calculation predicts

$\varepsilon \approx 1\text{GeV/fm}^3$

$T \approx 170\text{MeV}$

History of collision and photon emission



Direct photon analysis

All photons except for those originating from hadron decays.

- emitted during all stages of the collisions
- don't interact with the medium

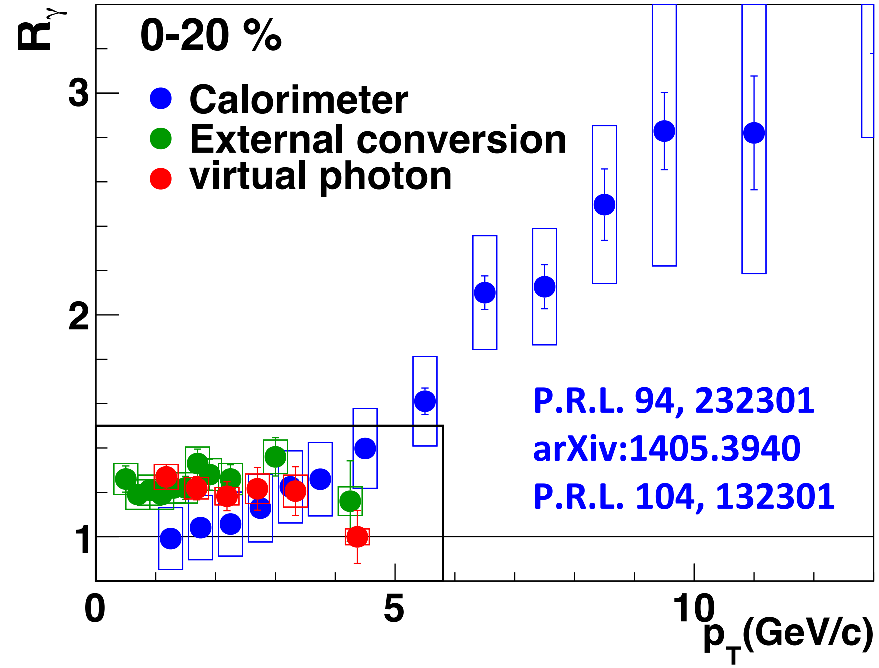
The excess of direct photon

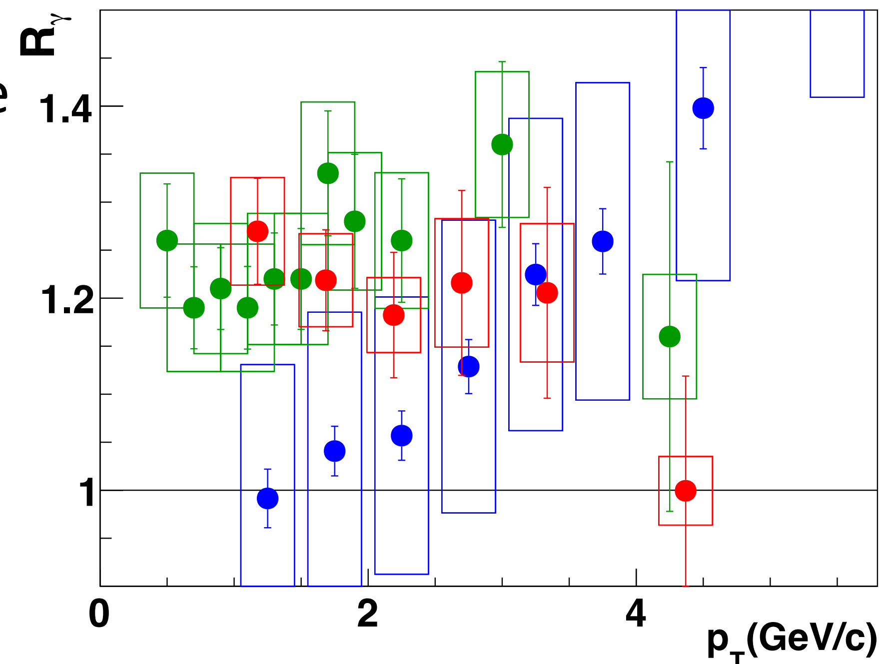
The excess of direct photon has been measured via several methods.

The virtual photon method and external conversion photon method are sensitive to low p_T region.

Less than 4 GeV/c, direct photons are included by 20 % in inclusive photon.

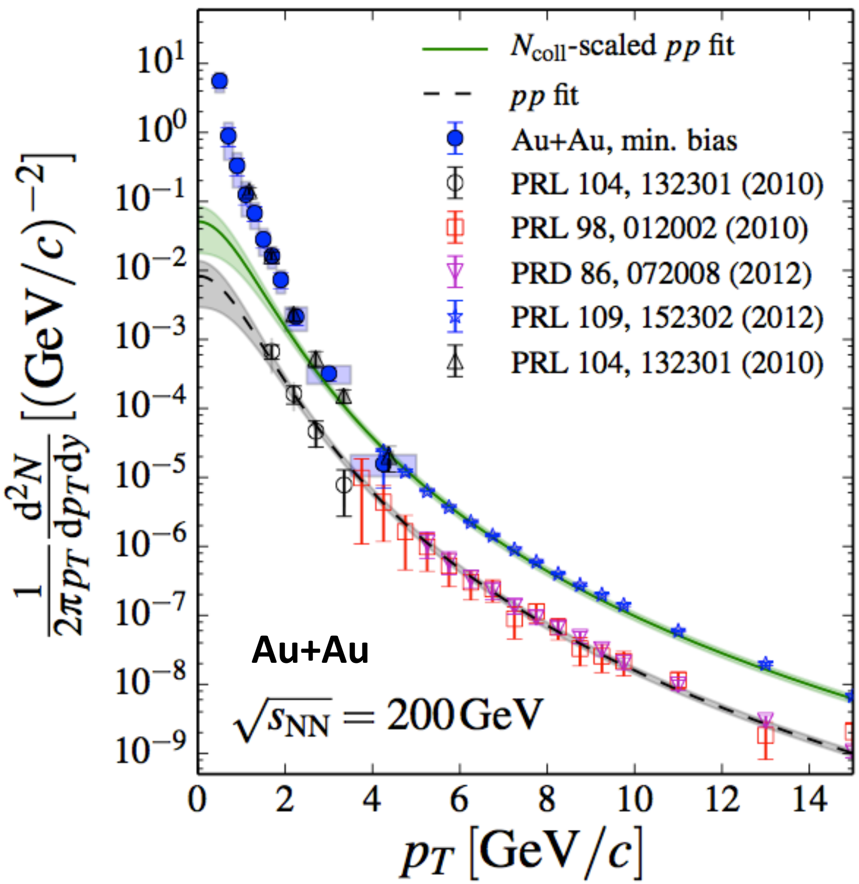
$$R_\gamma = N_{inc.}/N_{dec.}$$





Direct photon p_T spectra

arXiv:1405.3940(2014)



The p_T spectra in Au+Au collision is enhanced compared with that in p+p collision scaled by the number of binary collisions less than 4 GeV/c.

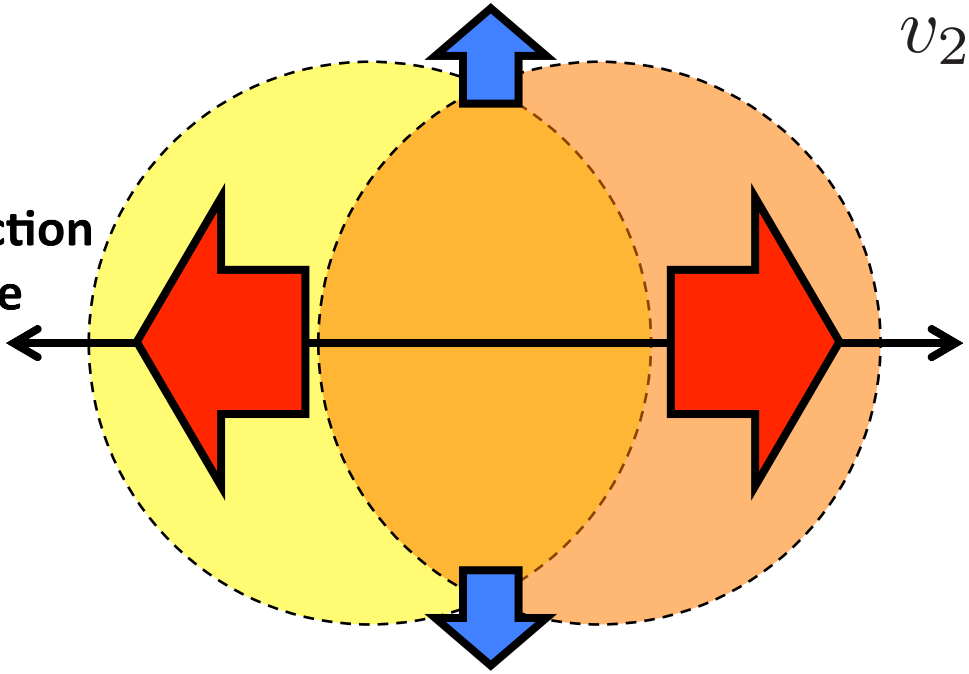
The excess of p_T spectra is fitted and effective temperature is extracted.
(Freeze out temperature ≈ 100MeV)

Centrality	Effective temperature
0% - 20%	239 ± 25 ± 7 (MeV)
20% - 40%	260 ± 33 ± 8 (MeV)
40% - 60%	225 ± 28 ± 6 (MeV)

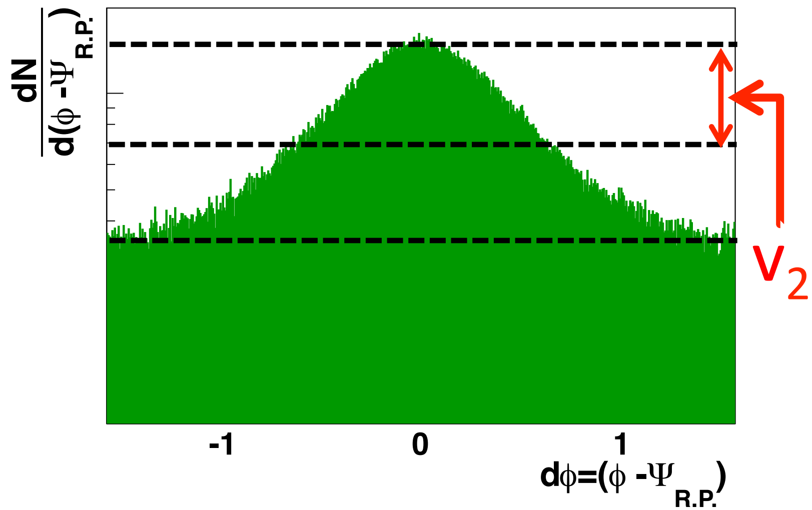
Photons in low p_T are mainly radiated from very hot medium at early time of collisions.

Azimuthal anisotropy (Elliptic flow)

$$v_2 = \langle \cos\{2(\phi - \Psi_{R.P.})\} \rangle$$



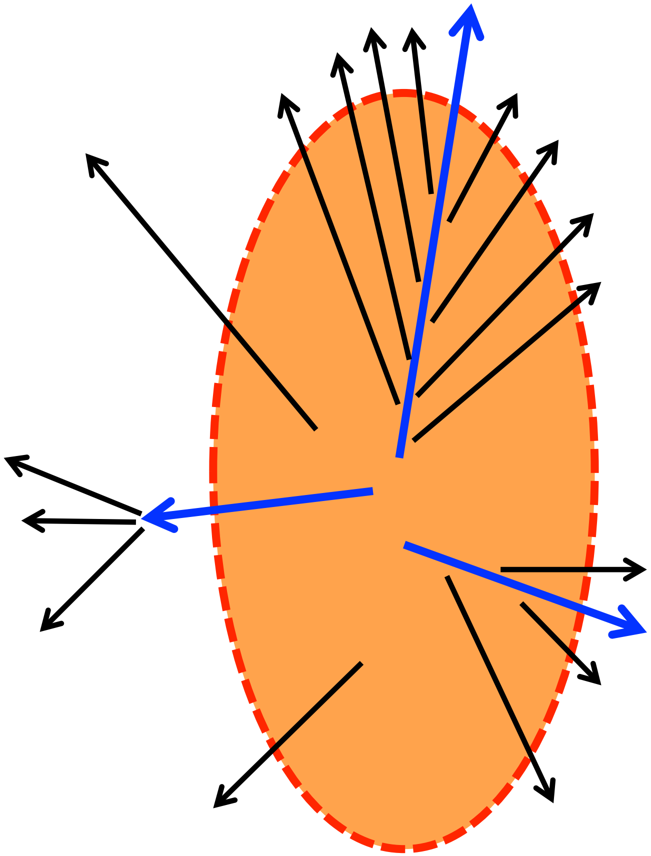
charged particle dϕ distribution



- anisotropic pressure gradient in participant zone (Initial state)
- QGP expansion (hydrodynamic motion, η/s)
  (η is shear viscosity and **s** is entropy density)
- hadron production mechanism (coalescence)

(1) : **Initial geometry** is converted into final azimuthal anisotropy
(2) : (expected to be) sensitive to η/s.

Photon emitting angle dependence



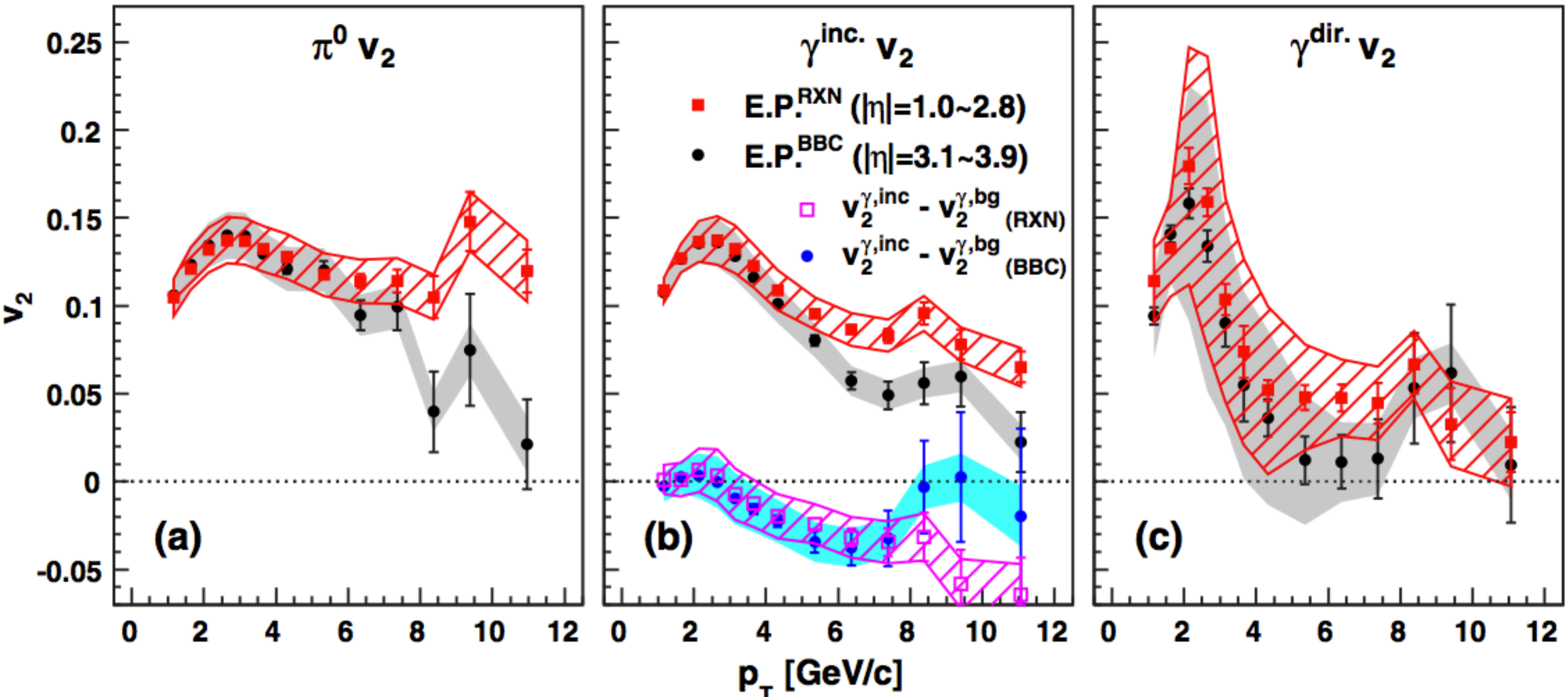
Angular dependence of photon sources

- Initial hard scattering : $v_2 \approx 0$
- Medium induced : $v_2 \leq 0$
- Jet fragmentation : $v_2 \geq 0$
- Radiation from expanding medium : $v_2 > 0$

The measurement of photon azimuthal anisotropy is a powerful probe to identify the photon sources.

Elliptic flow of direct photon

P.R.L. 109, 122302(2012)



High p_T: very small v_2

It is consistent with expectation that photons produced in the initial hard scattering are dominant.

Low p_T : Comparable to hadron v_2 at around 2 GeV/c

Direct photon puzzle

Thermal radiation photons are dominant in low p_T region.

Elliptic flow :

Photon should have small v_2, since it includes one from early stage having small v_2,

-> Photons are dominantly emitted at **late stage**.

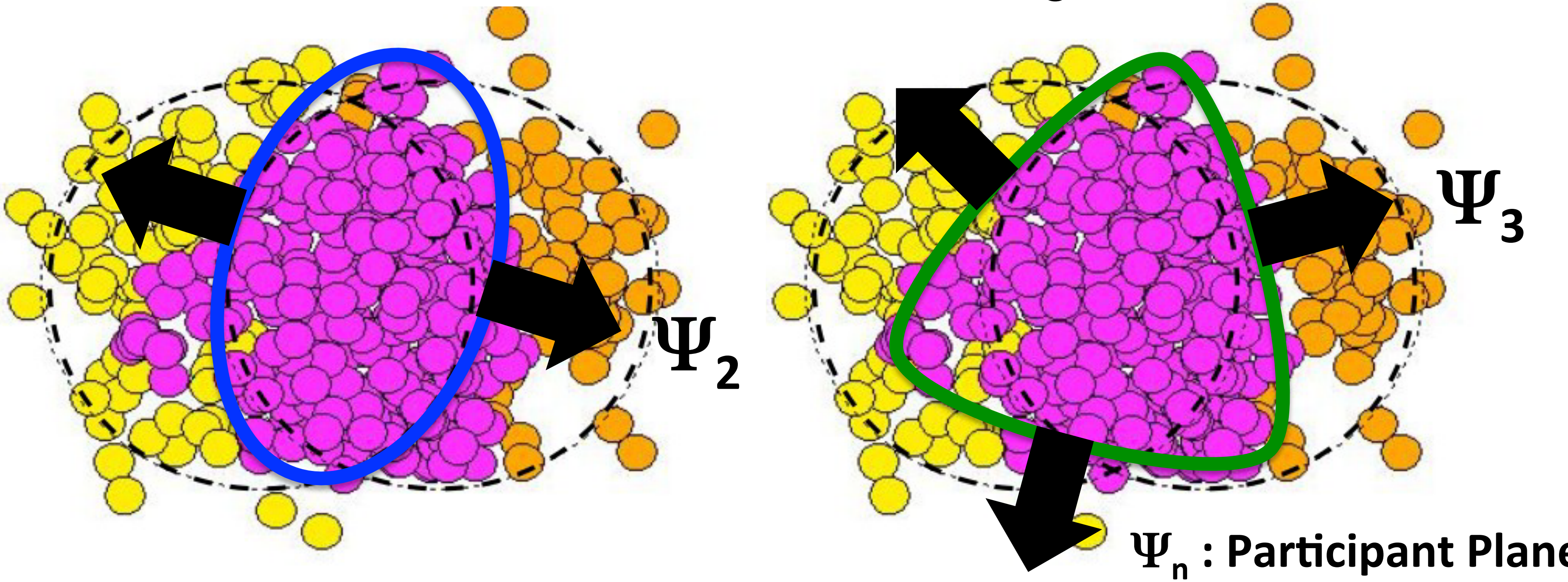
p_T spectra :

Emitted from very hot medium (T_{eff}≈240MeV).

-> Photons are dominantly emitted at **early stage**.

There is a discrepancy, and it is called "**direct photon puzzle**".
There is no models to explain both observables simultaneously.

Third order azimuthal anisotropy (v_3)



$$N(\phi - \Psi_n) \propto 1 + 2\sum v_n \cos\{n(\phi - \Psi_n)\}$$

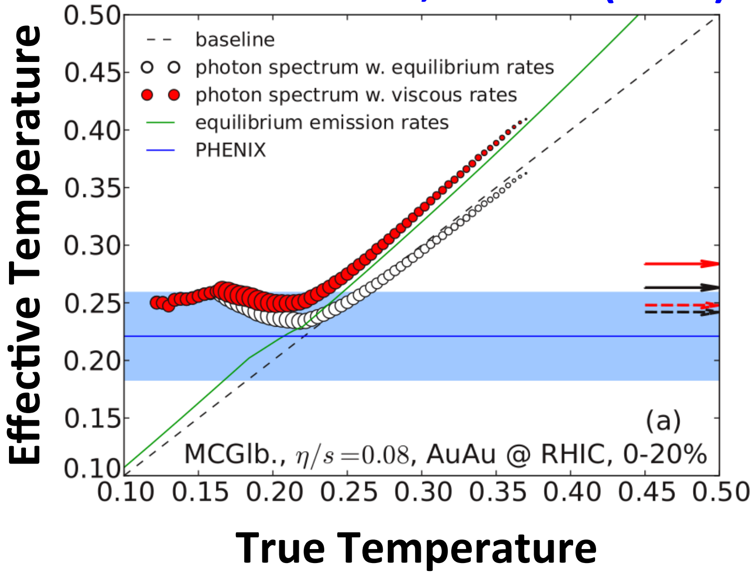
$$v_n = \langle \cos\{n(\phi - \Psi_n)\}\rangle$$

v_3 is originating from fluctuation of the shape of participants.
The higher order flow is expected to constrain the initial geometry calculating model and η/s of QGP.

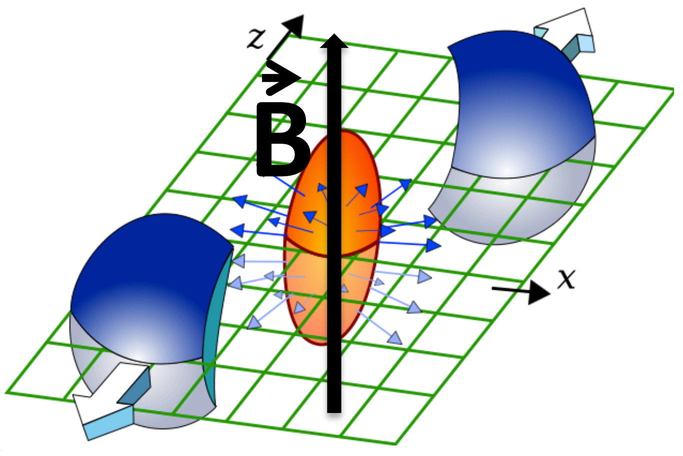
Why direct photon v_3 is measured?

Radial flow effect (blue shift effect) :
It makes effective temperature higher than true temperature.
Photons from late state are dominant.
v_2>0 : v_3>0

P.R.C 89, 044910 (2014)



Large magnetic field :
Direction of magnetic field is strongly related with Ψ_2(R.P.) but not with Ψ_3.
v_2>0 : v_3≈0



v_3 measurement could provide additional constraint on photon production mechanism.

My activity

Poster & Talk : Analysis

2012 (D1): Data taking shift and Detector expert & TOF calibration

Poster QM 2012 | **Talk** ATHIC 2012 | **Talk** JPS spring

Identified particle azimuthal anisotropy

2013 (D2): Data taking shift and Detector expert & TOF calibration

Talk JPS fall | **Talk** JPS spring

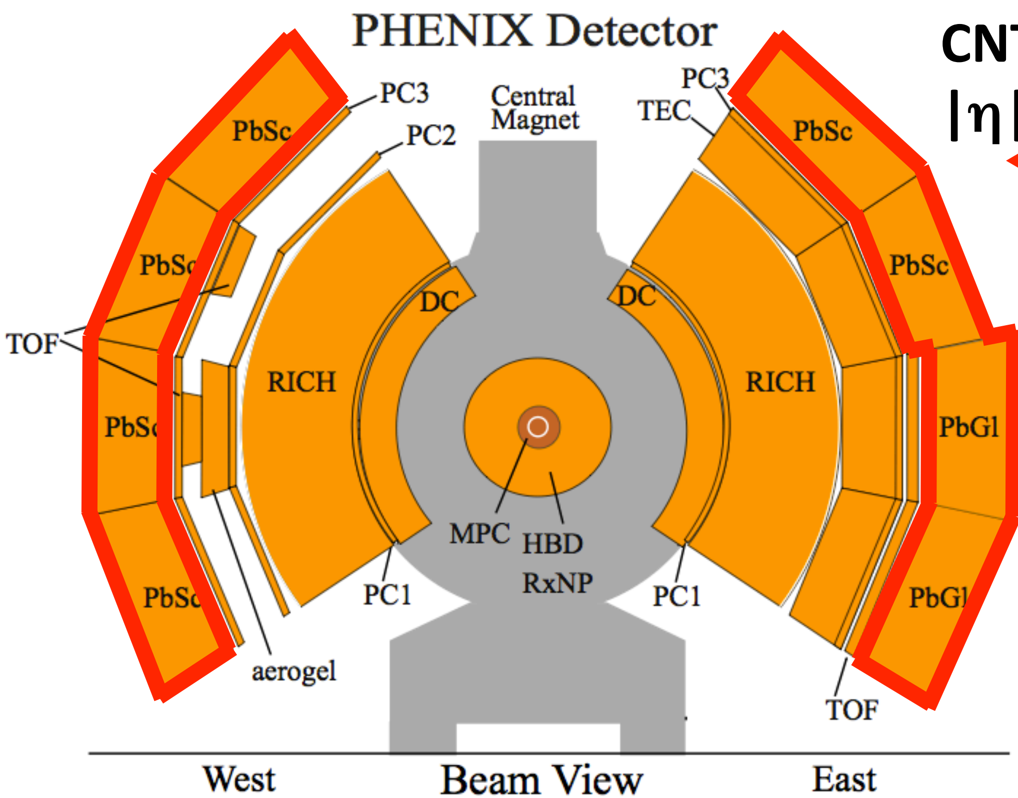
Neutral pion and direct photon azimuthal anisotropy

2014 (D3): Data taking shift and Detector expert

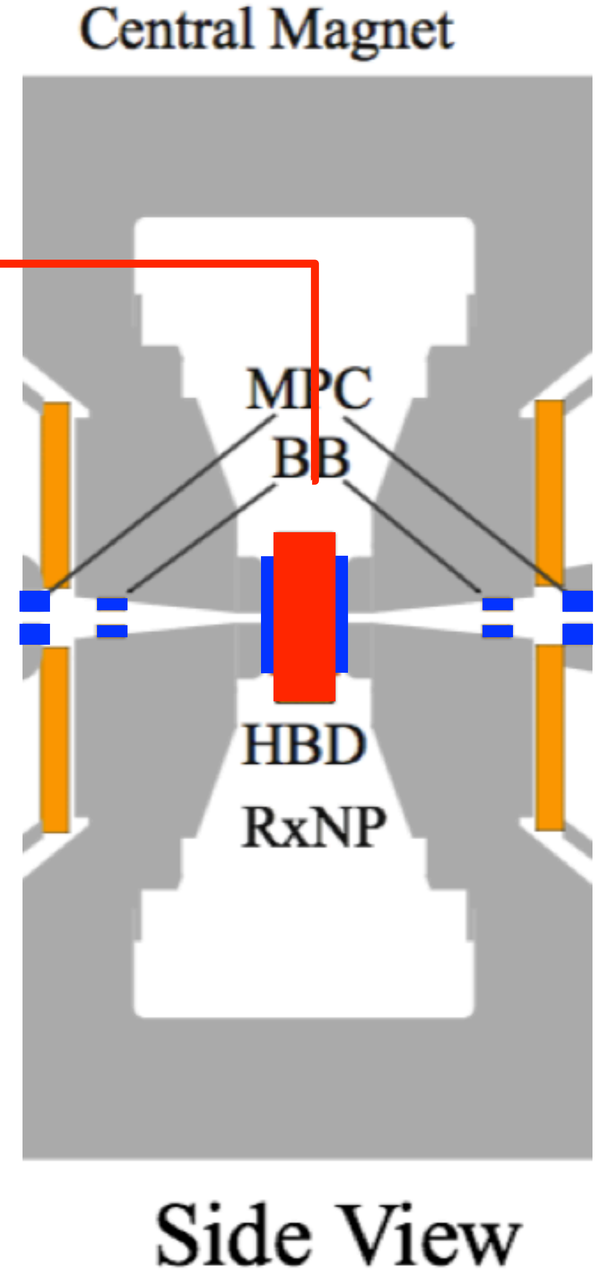
Talk QM 2014 | **Talk** HIC HIP | **Talk** ATHIC 2014 | **Talk** WPCF 2014

Analysis

PHENIX detector



CNT
|η| <0.35



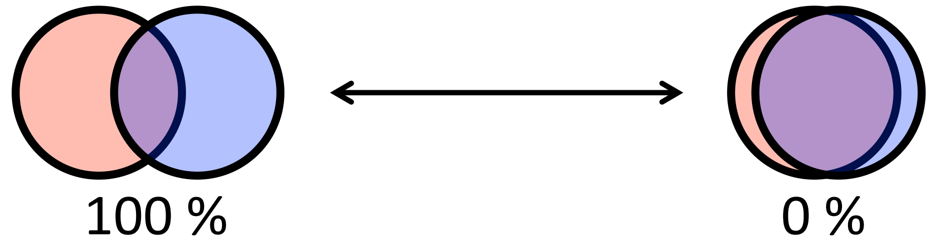
Reaction Plane detector (RxNP), MPC, BBC are used for measuring Event Plane.

Photons and π^0 are detected by EMCal in CNT.

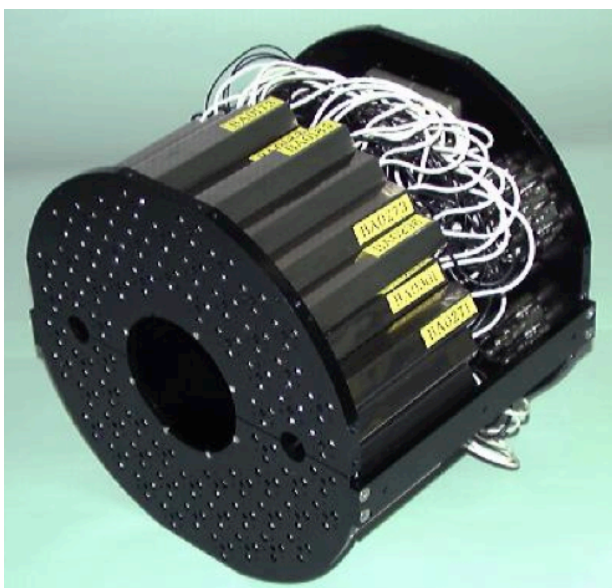
$$v_n = \langle \cos\{n(\phi - \Psi_n)\}\rangle$$

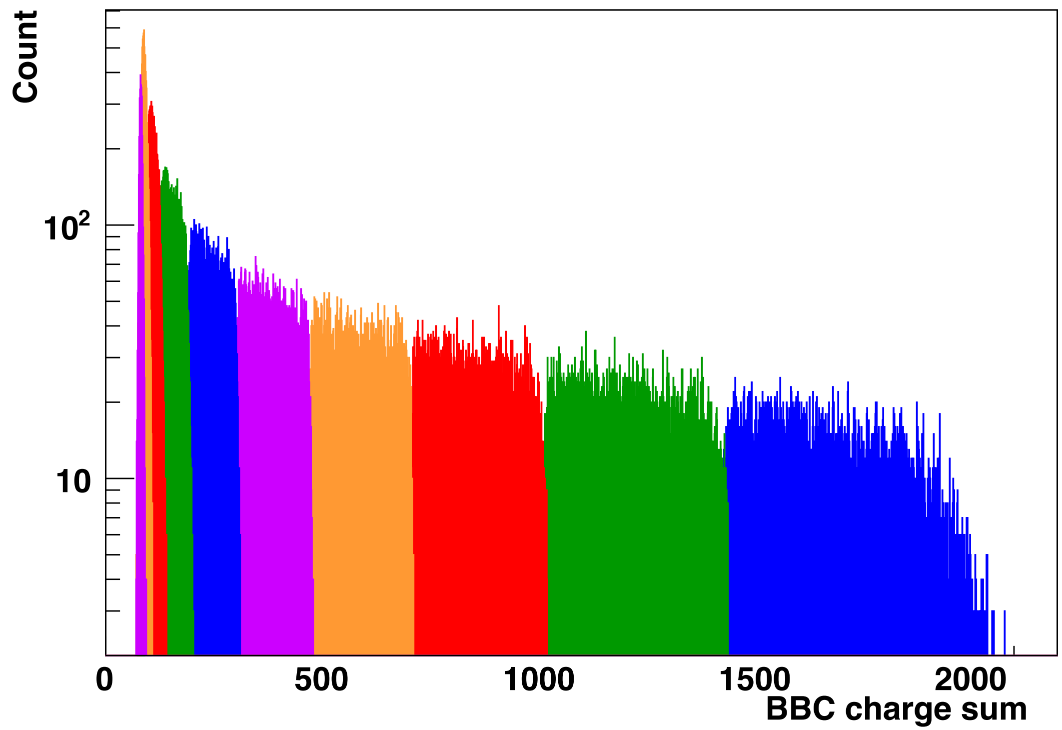
Centrality determination

Centrality :
The size of participant zone is classified by multiplicity in BBC.



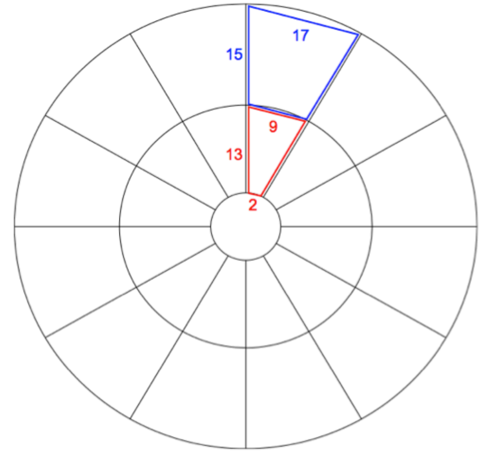
Beam-Beam Counter (BBC) :
Measures charged particles.





Event plane and resolution

Reaction Plane detector(RxN)



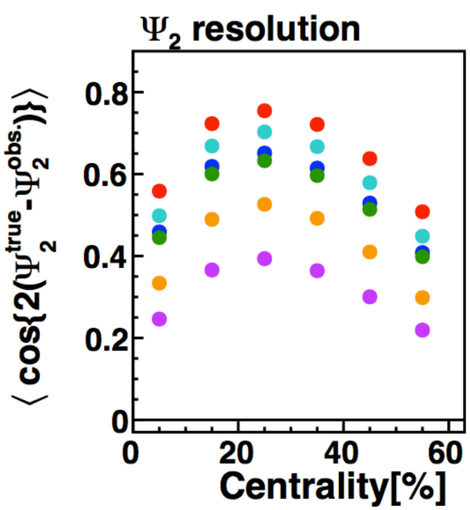
Event plane is determined for each harmonic "n".

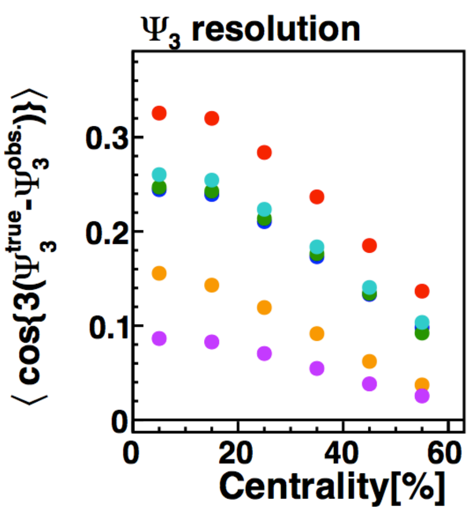
$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\sum w_i \sin n\phi_i}{\sum w_i \cos n\phi_i}\right)$$

$$Res(\Psi_n) = \langle \cos\{n(\Psi_n^{true} - \Psi_n^{obs.})\}\rangle$$

$$v_n^{true} = v_n^{obs.}/Res(\Psi_n)$$

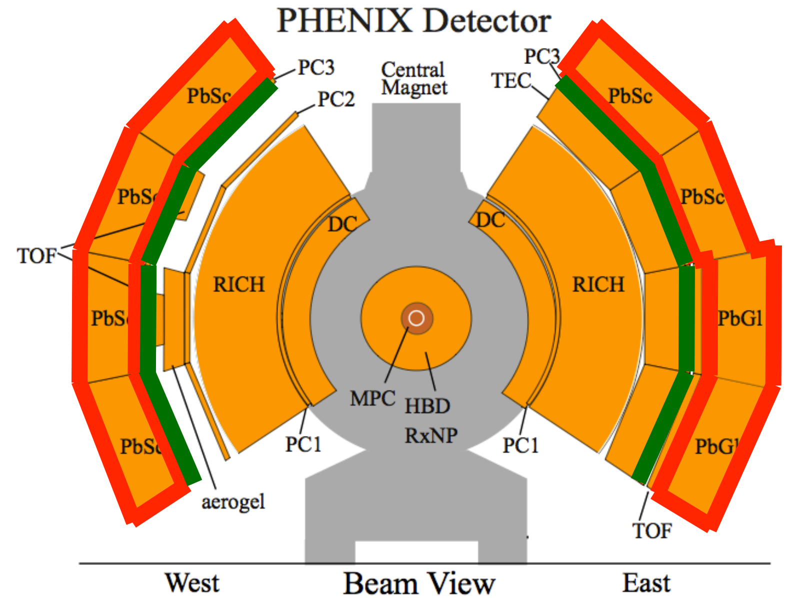
Muon Piston Calorimeter (MPC)





RxN(In) MPC
RxN(Out) BBC
RxN(I+O) RxN(In)+MPC

Photon reconstruction



Pad chamber : space point of charged particle track

Electromagnetic calorimeter(EMCal)

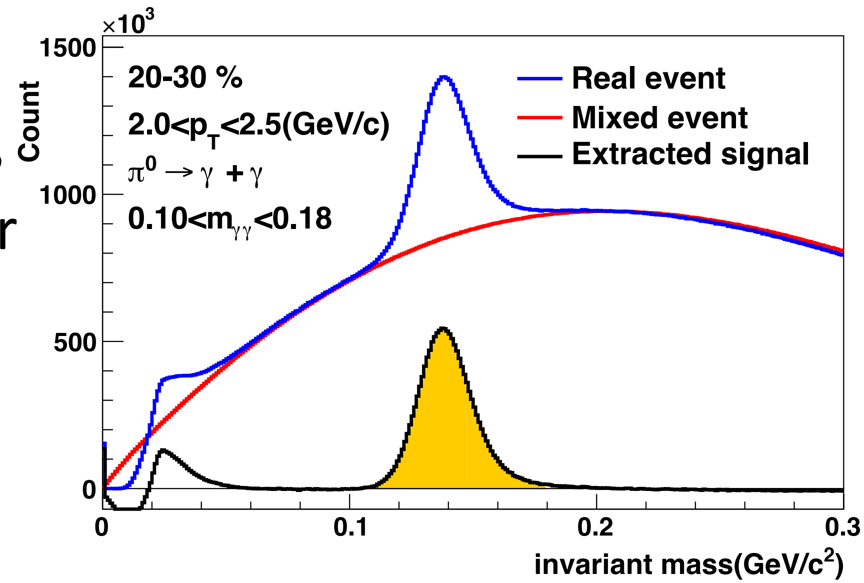
Photons are reconstructed

- Energy threshold : E > 0.2GeV
- Shower shape : $\chi^2 < 3$
- Charged particle rejection at PC3 : $\sqrt{(dz)^2+(r_T\sin(d\phi))^2} > 6.5$

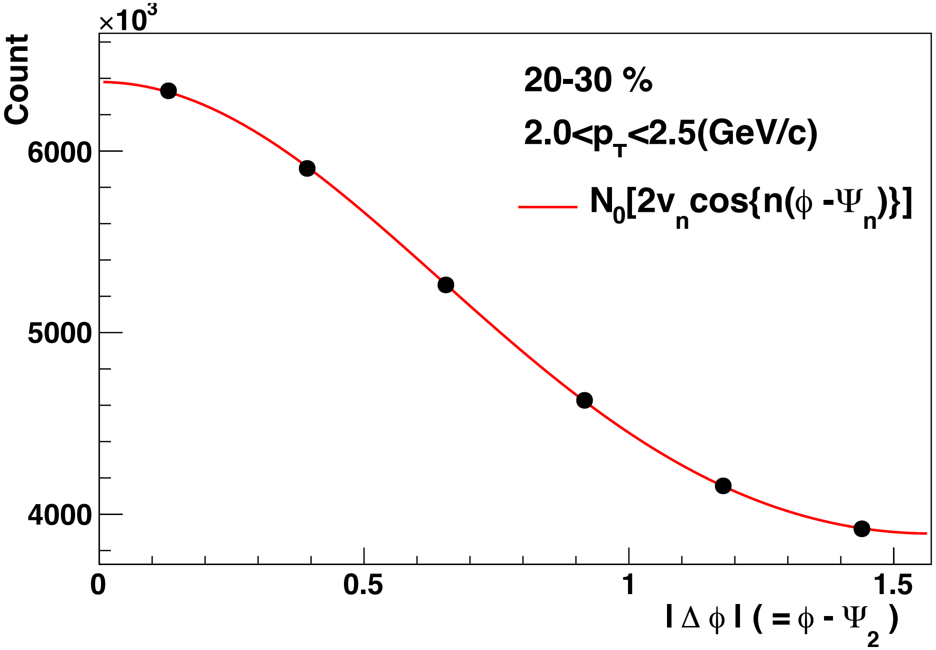
π^0 (->$\gamma+\gamma$) reconstruction

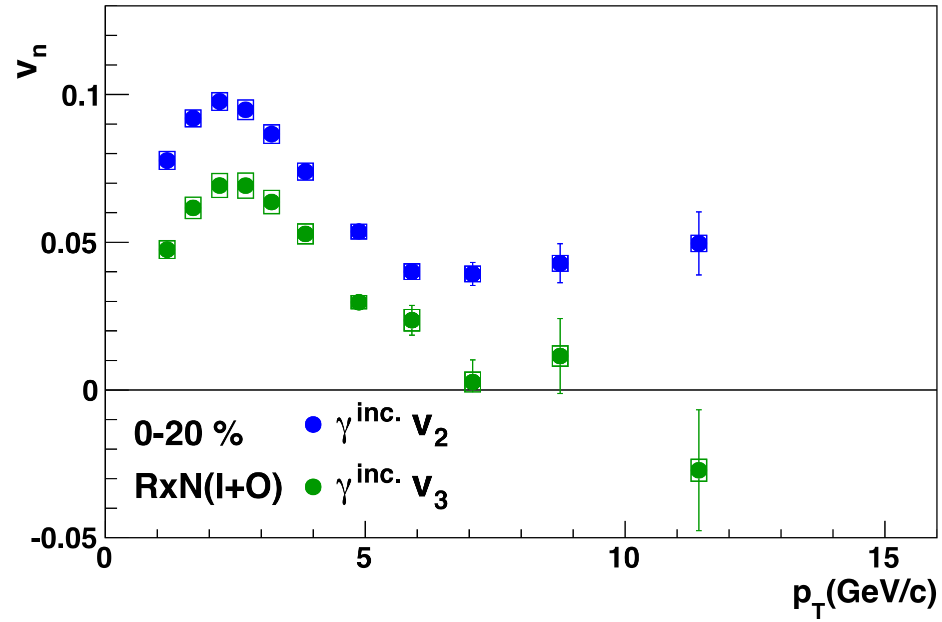
- Asymmetry cut : $|E_1-E_2|/(E_1+E_2)<0.8$
- Photons are detected in same sector
- Invariant mass of $\gamma+\gamma$

$$Mass = \sqrt{2E_1E_2(1-\cos\theta)}$$



Inclusive photon v_n measurement





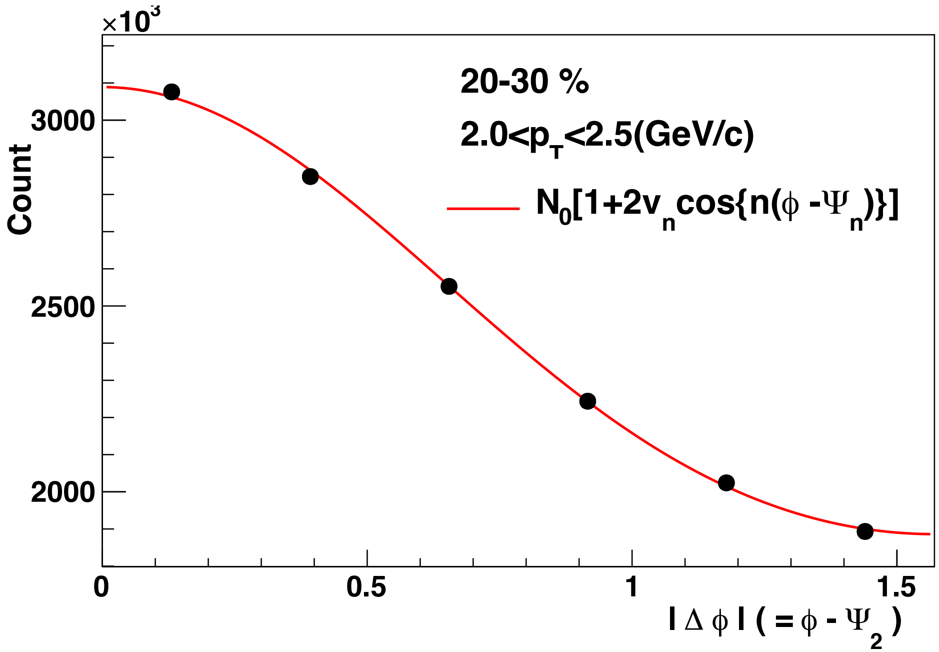
The method of extracting v_n

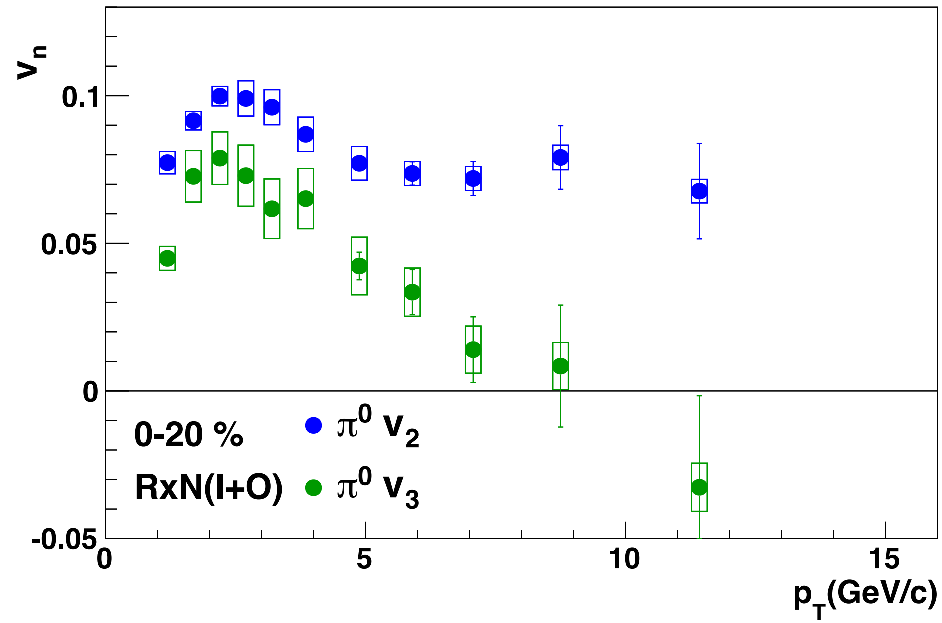
1. $v_n = \langle \cos\{n(\phi - \Psi_n)\} \rangle$
2. $dN/d\phi$ is fitted by $N_0(1+2v_n\cos\{n(\phi-\Psi_n)\})$

<u>Systematic uncertainty</u>

- Photon selection
- v_n measuring method
- Event plane determination

Neutral pion v_n measurement





The number of π^0 is counted with respect to the event plane.
The azimuthal distribution is fitted by the equation.

$$N_0(1 + 2v_n \cos\{n(\phi - \Psi_n)\})$$

<u>Systematic uncertainty</u>

- Photon selection
- π^0 selection
- Event plane determination

Hadronic decay photon

It is impossible to identify photons originating from hadron decay experimentally.
Decay photon p_T spectra and v_n should be simulated by Monte-Carlo simulation.

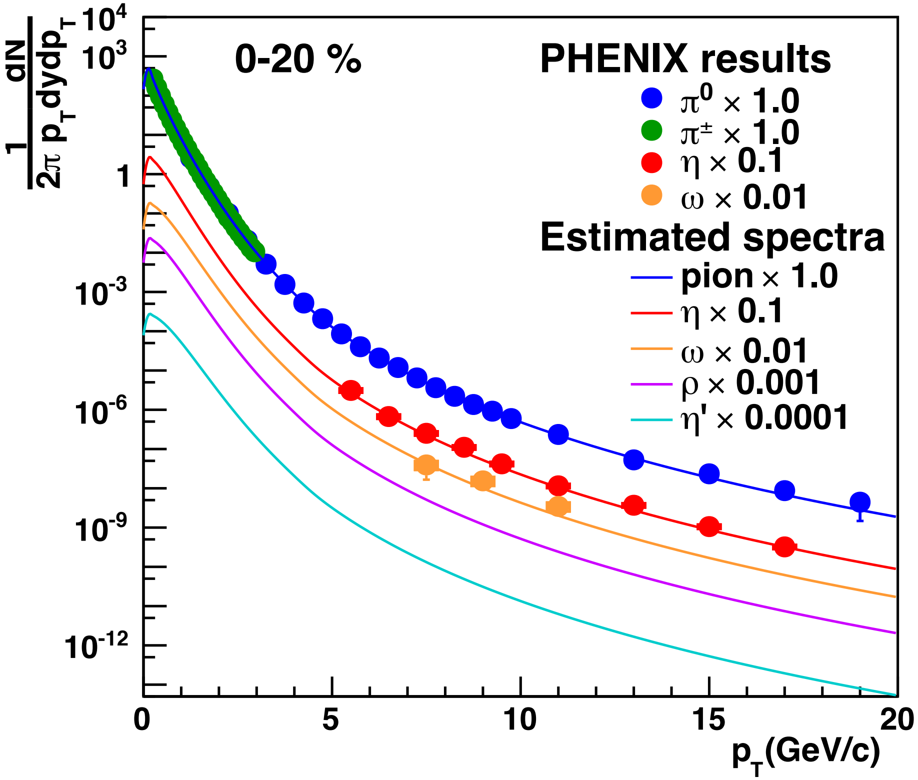
Particle Data Group

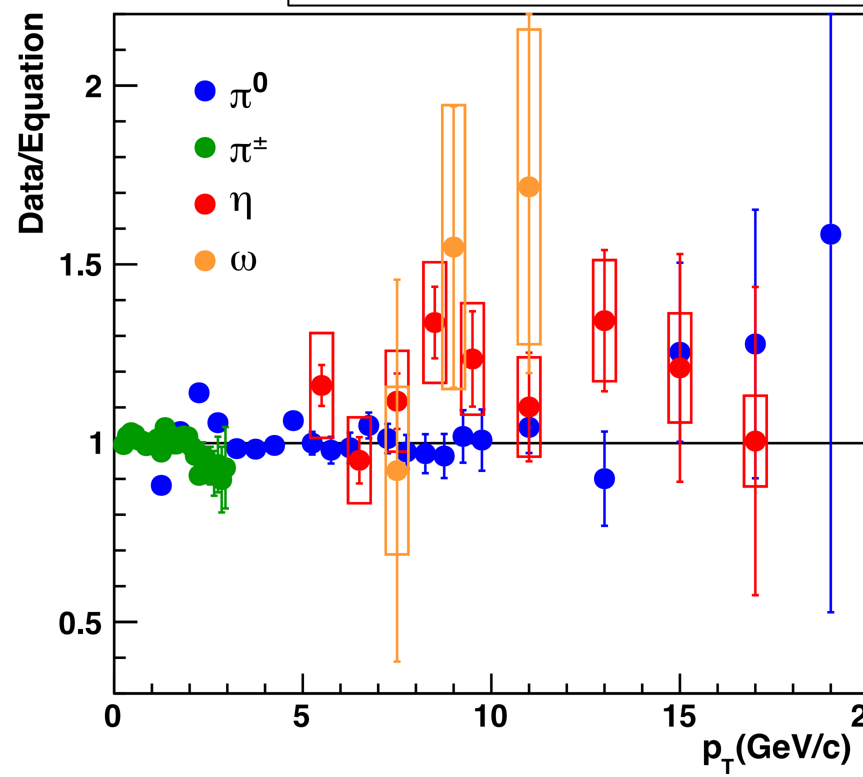
meson	invariant mass(MeV/c^2)	decay mode	branching ratio
π^0	134.98	2γ	(98.823 $\pm$ 0.034) %
		$e^+e^-\gamma$	(1.174 $\pm$ 0.035) %
η	547.86	2γ	(39.41 $\pm$ 0.20) %
		$\pi^+\pi^-\gamma$	(4.22 $\pm$ 0.08) %
		$e^+e^-\gamma$	(6.9 $\pm$ 0.4) $\times 10^{-3}$
		$\pi^0 2\gamma$	(2.7 $\pm$ 0.5) $\times 10^{-4}$
ω	782.65	$\pi^0\gamma$	(8.28 $\pm$ 0.28) %
ρ	775.26	$\pi^+\pi^-\gamma$	(9.9 $\pm$ 1.6) $\times 10^{-3}$
		$\pi^0\gamma$	(6.0 $\pm$ 0.8) $\times 10^{-4}$
η'	957.78	$\rho\gamma$	(29.1 $\pm$ 0.5) %
		$\omega\gamma$	(2.75 $\pm$ 0.23) %
		2γ	(2.20 $\pm$ 0.08) %
		$\mu^+\mu^-\gamma$	(1.08 $\pm$ 0.27) $\times 10^{-4}$

Meson p_T spectra estimation

$$p_{T,meson} = \sqrt{p_{T,pion}^2 + M_{meson}^2 - M_{pion}^2}$$

$$\begin{aligned} \frac{d\sigma}{p_T dp_T} &= T(p_T)F_0 + (1 - T(p_T))F_1, \\ T(p_T) &= \frac{1}{1 + \exp\{(p_T - t)/w\}}, \\ F_0 &= \frac{c}{\{\exp(-ap_T - bp_T^2) + p_T/p_0\}^n}, \\ F_1 &= \frac{A}{p_T^m}, \end{aligned}$$





Since it is difficult to measure mesons except for pion, the other mesons p_T spectra are estimated by m_T scaling from pion experimental data.

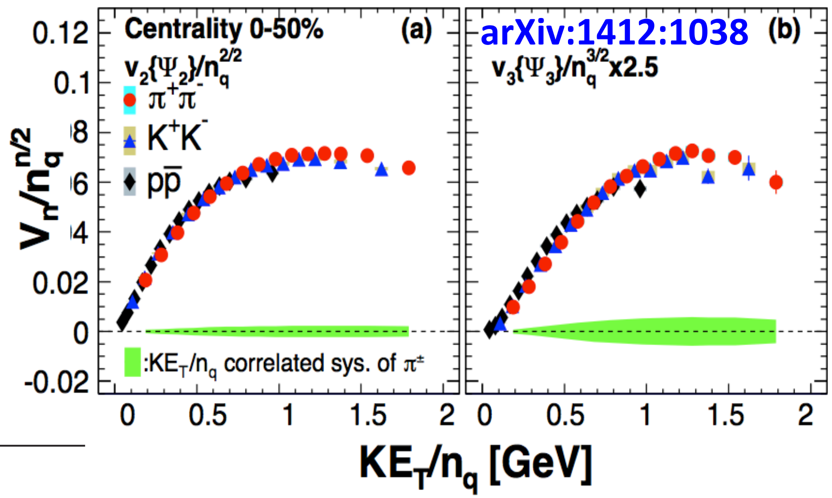
P.R.C 69,034909
P.R.L. 101,232301
P.R.C 82,011902
P.R.C 84,044902

Meson v_n estimation

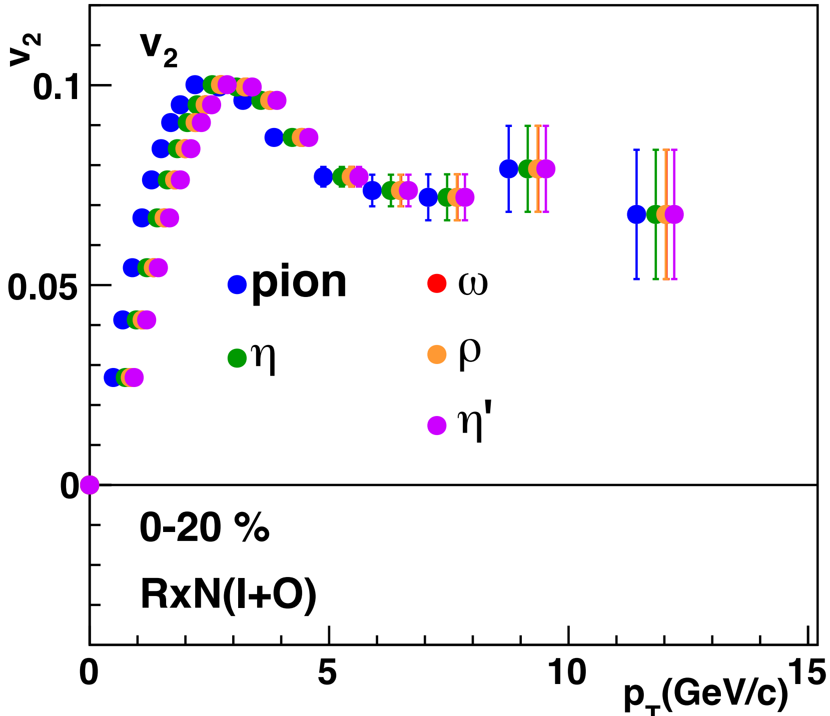
It is known that hadron v_n as a function of KE_T are scaled by the number of constituent quark.

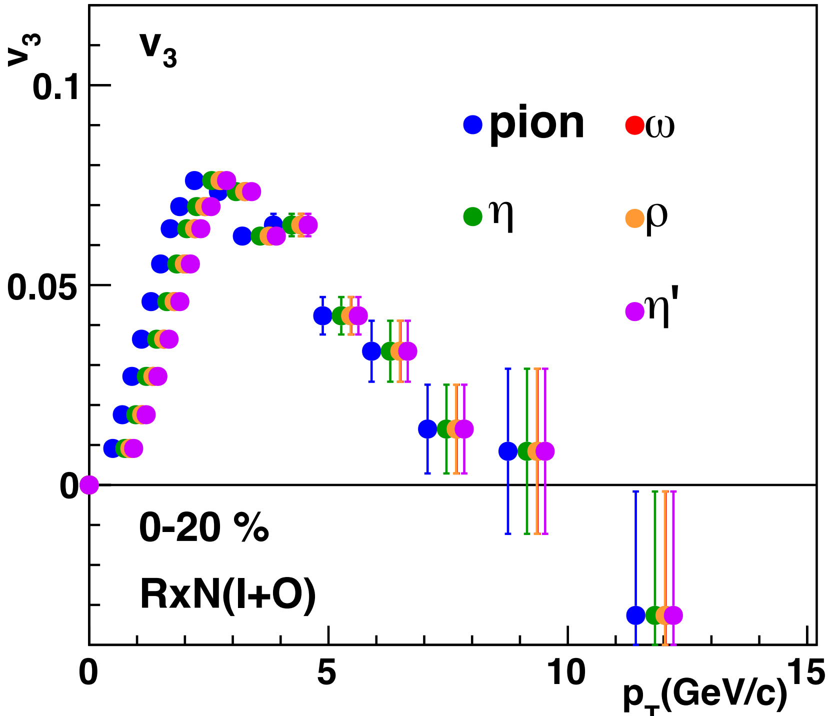
Meson v_n is estimated from pion v_n.

The number of constituent scaling

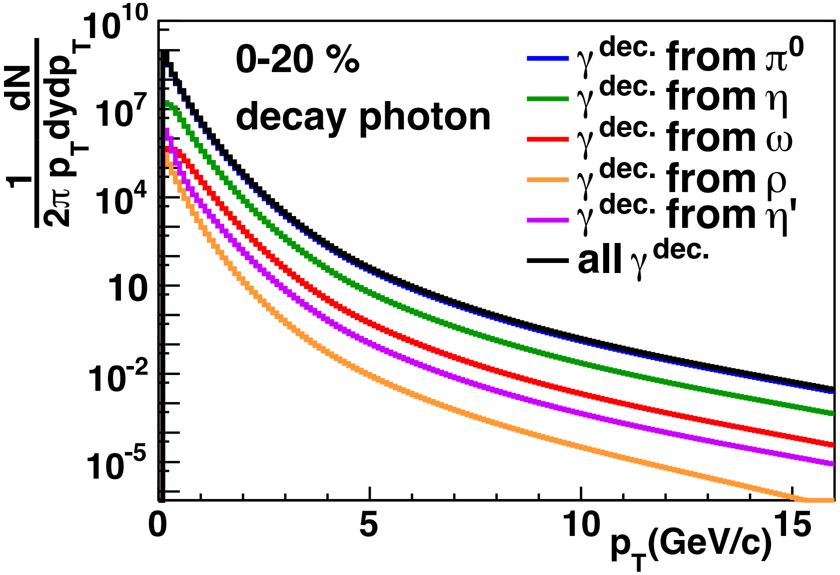


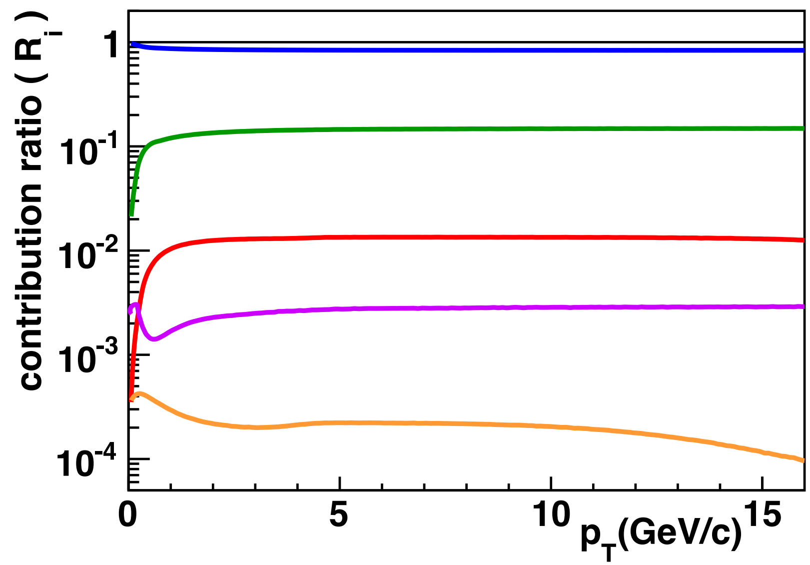
$$p_{T,meson} = \sqrt{\left(\sqrt{p_{T,\pi}^2 + M_\pi^2} - M_\pi + M_{meson}\right)^2 - M_{meson}^2}$$

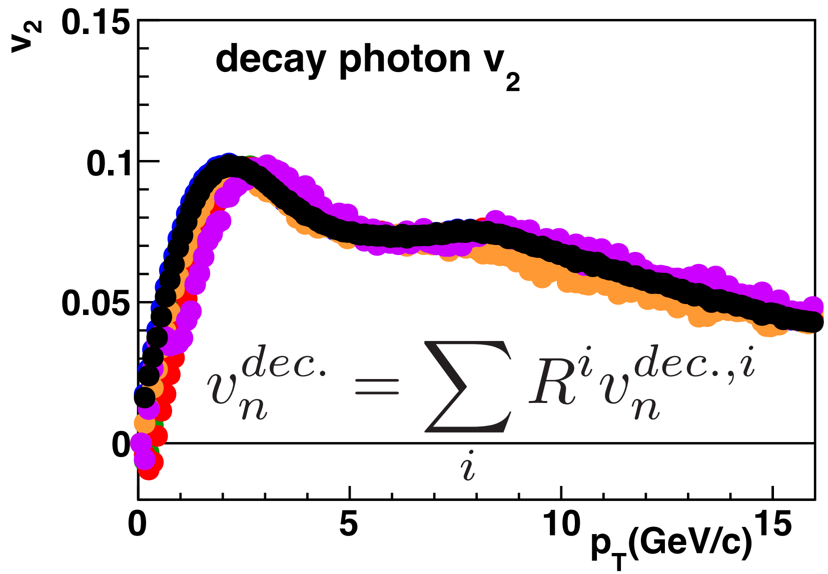




Hadronic decay photon v_n





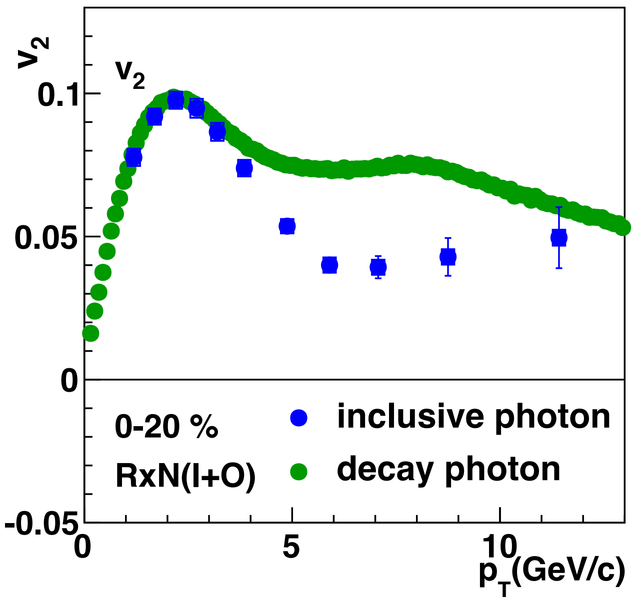


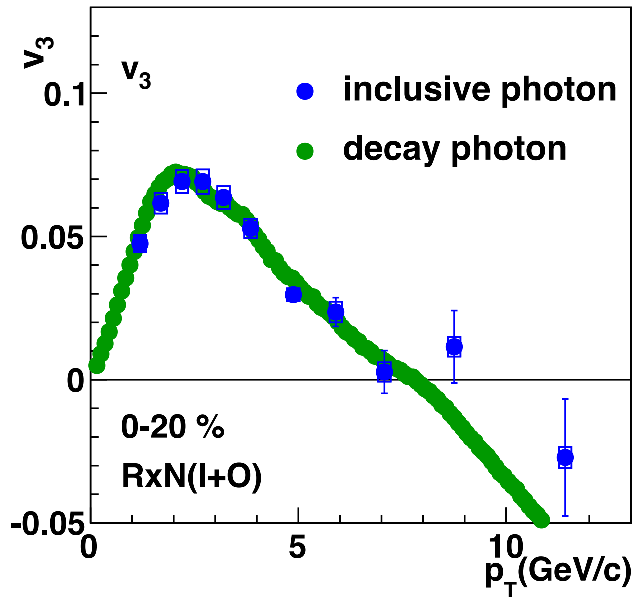
Decay photon v_n is simulated from meson input.

Systematic uncertainty

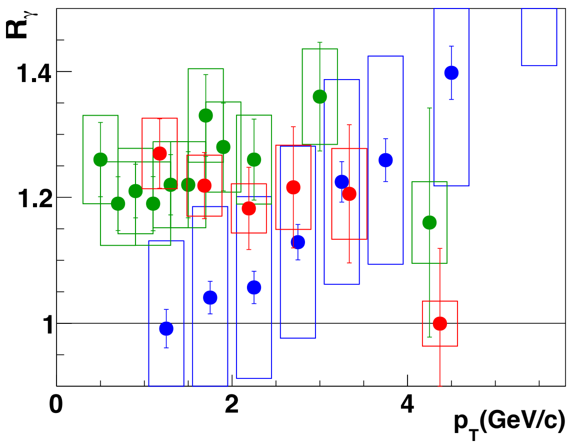
- Propagated from pion p_T spectra
- Propagated from pion v_n
- Event plane determination

Direct photon v_n

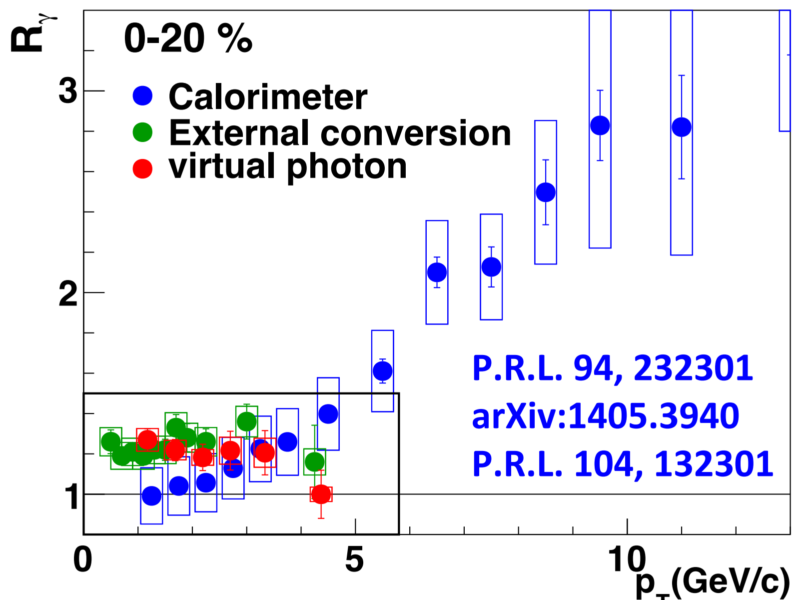




$$R_\gamma = N_{inc.}/N_{dec.}$$



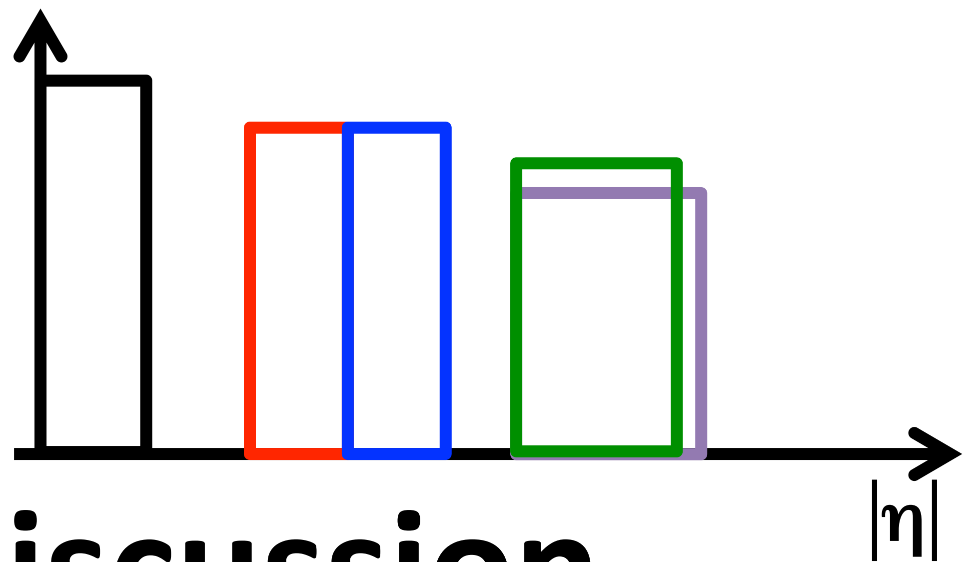
$$\nu_n^{dir.} = \frac{R_\gamma \nu_n^{inc.} - \nu_n^{dec.}}{R_\gamma - 1}$$



Systematic uncertainty

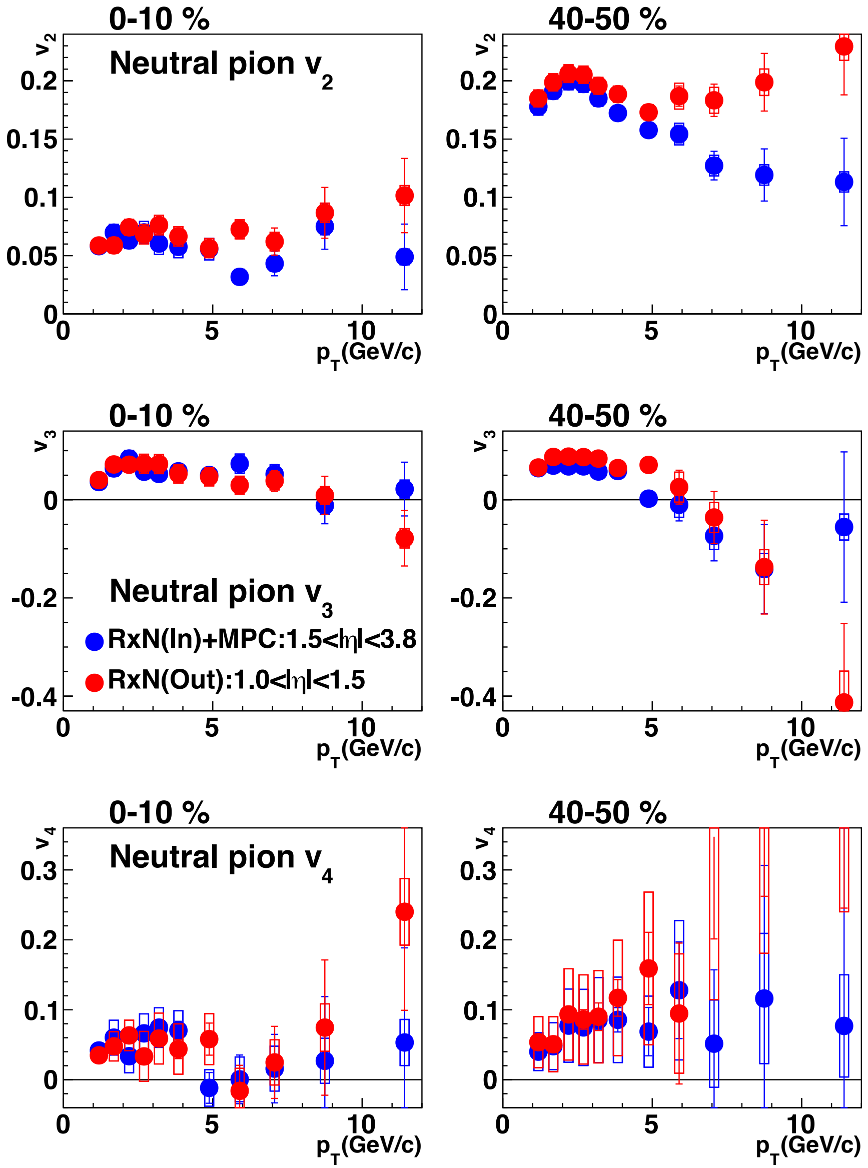
- Propagated from inclusive photon v_n
- Propagated from decay photon v_n
- Propagated from R_γ
- Event plane determination

Electromagnetic calorimeter (CNT)	$\lvert\eta\rvert < 0.35$
Reaction Plane detector (Inner)	$1.5 < \lvert\eta\rvert < 2.8$
Reaction Plane detector (Outer)	$1.0 < \lvert\eta\rvert < 1.5$
MPC	$3.1 < \lvert\eta\rvert < 3.8$
BBC	$3.0 < \lvert\eta\rvert < 3.9$



Results & Discussion
Neutral pion v_n

The event plane dependence of neutral pion v_n



Hadrons in high p_T are originated from jet fragmentation.

- Study jet property

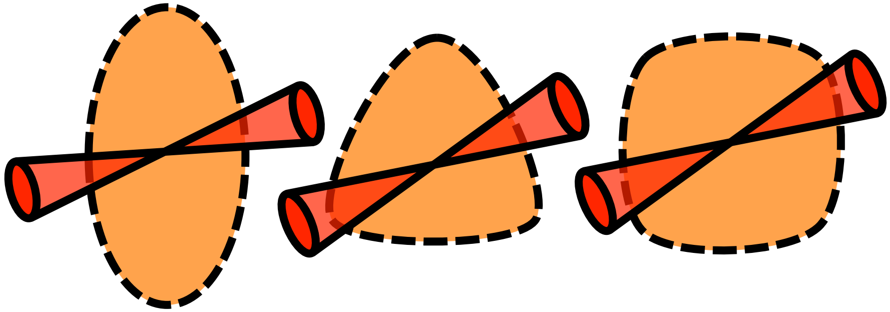
In peripheral event

v_2 and v_4 : positive

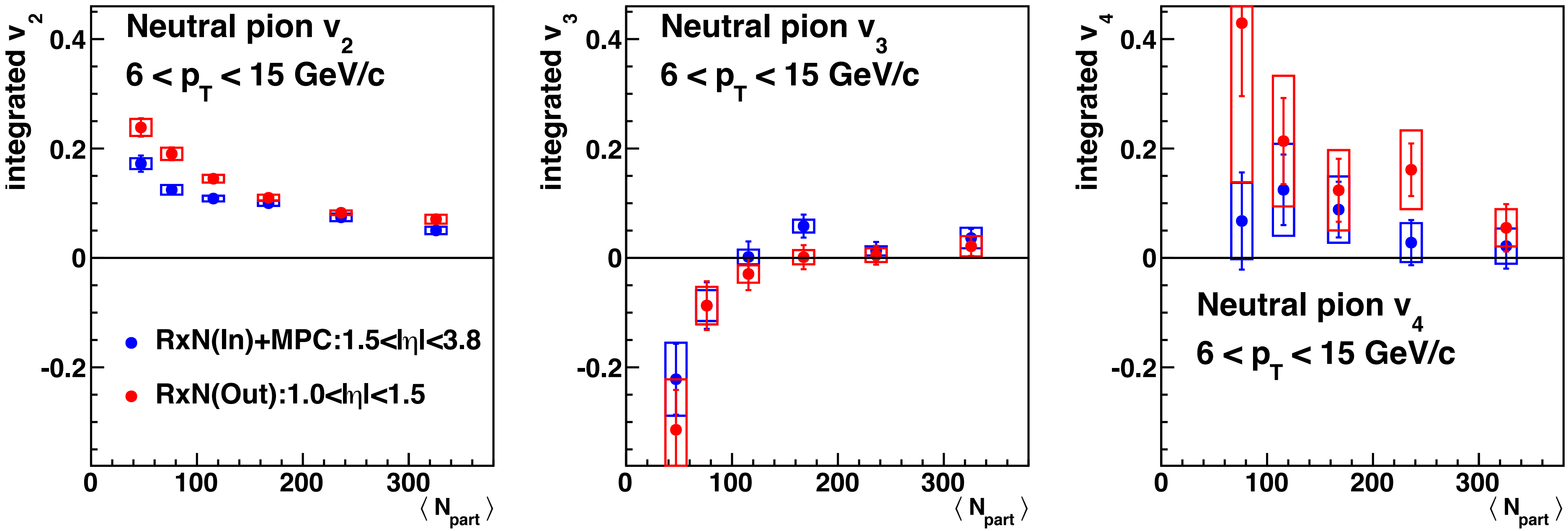
v_3 : negative

In the v_2 case,

there is the difference blue and red



Event plane dependence of π^0 v_n in high p_T

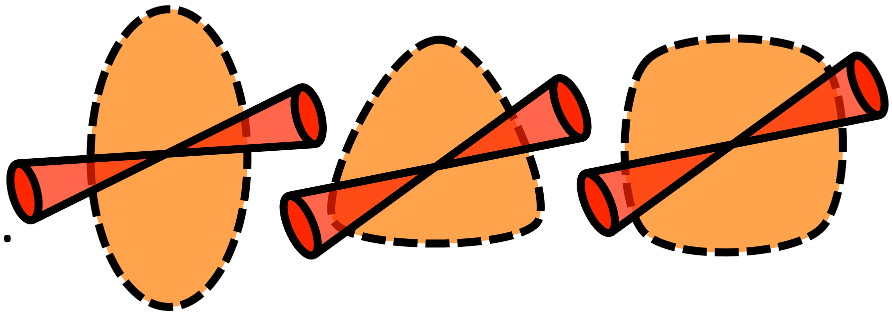


Di-jet makes $v_{2,4}$ >0 and v_3≈0.

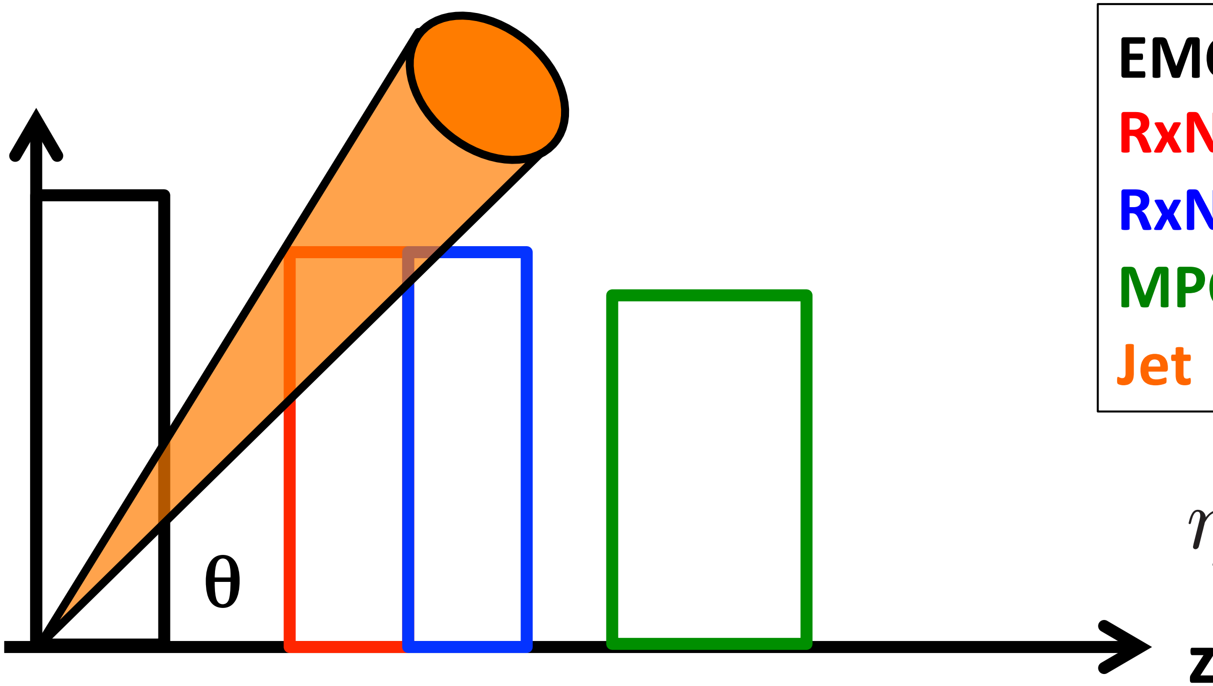
Energy loss of path length dependence : v_n > 0

It can be understood in central event.

Negative v_3 and the difference of red and blue in v_2 are not understood.



Jet effect in event plane determination



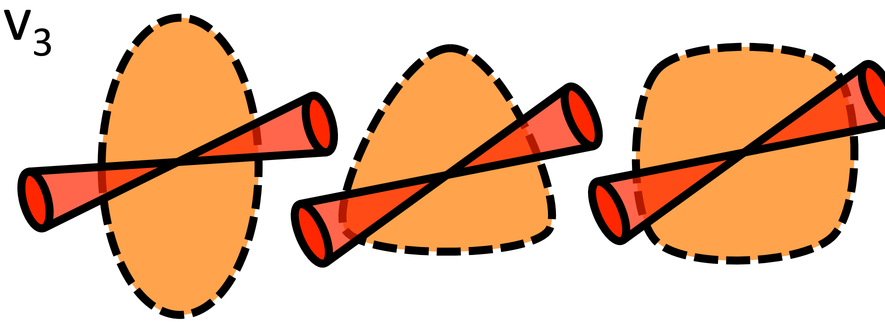
EMCal : |η|<0.35
RxN(Out) : 1.0<|η|<1.5
RxN(In) : 1.5<|η|<2.8
MPC : 3.1<|η|<3.8
Jet

$$\eta = -\ln\left\{\tan\frac{\theta}{z}\right\}$$

Event plane determination is much affected by jet effect in peripheral event due to small multiplicity.

The trend is different in v_2 & v_4 and v_3 due to the initial geometry.

v_2&v_4 > 0 : v_3 < 0



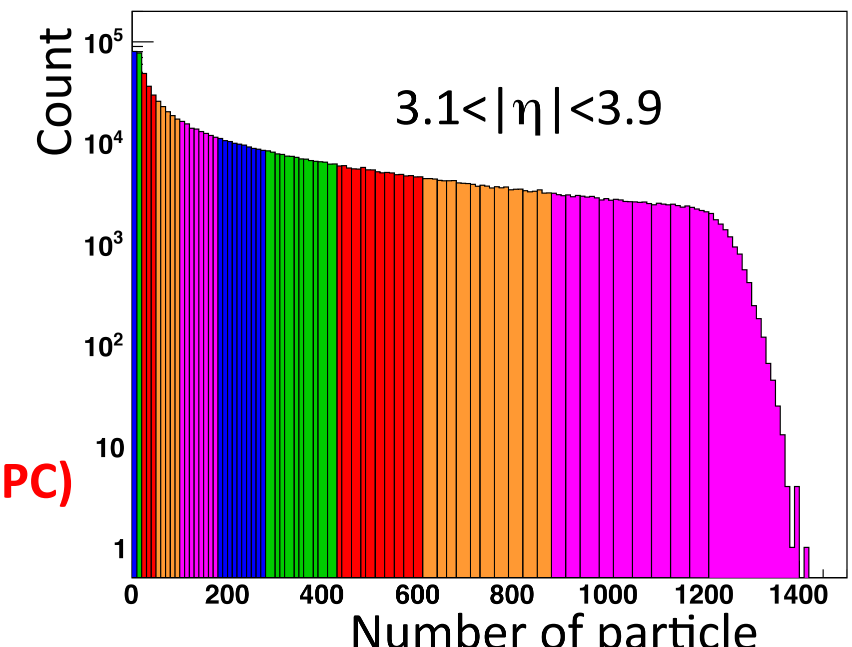
a Multiphase transport model (AMPT)

event generator (HIJING) + parton cascade (ZPC) + hadronization + hadron cascade
P.R.C 72, 064901

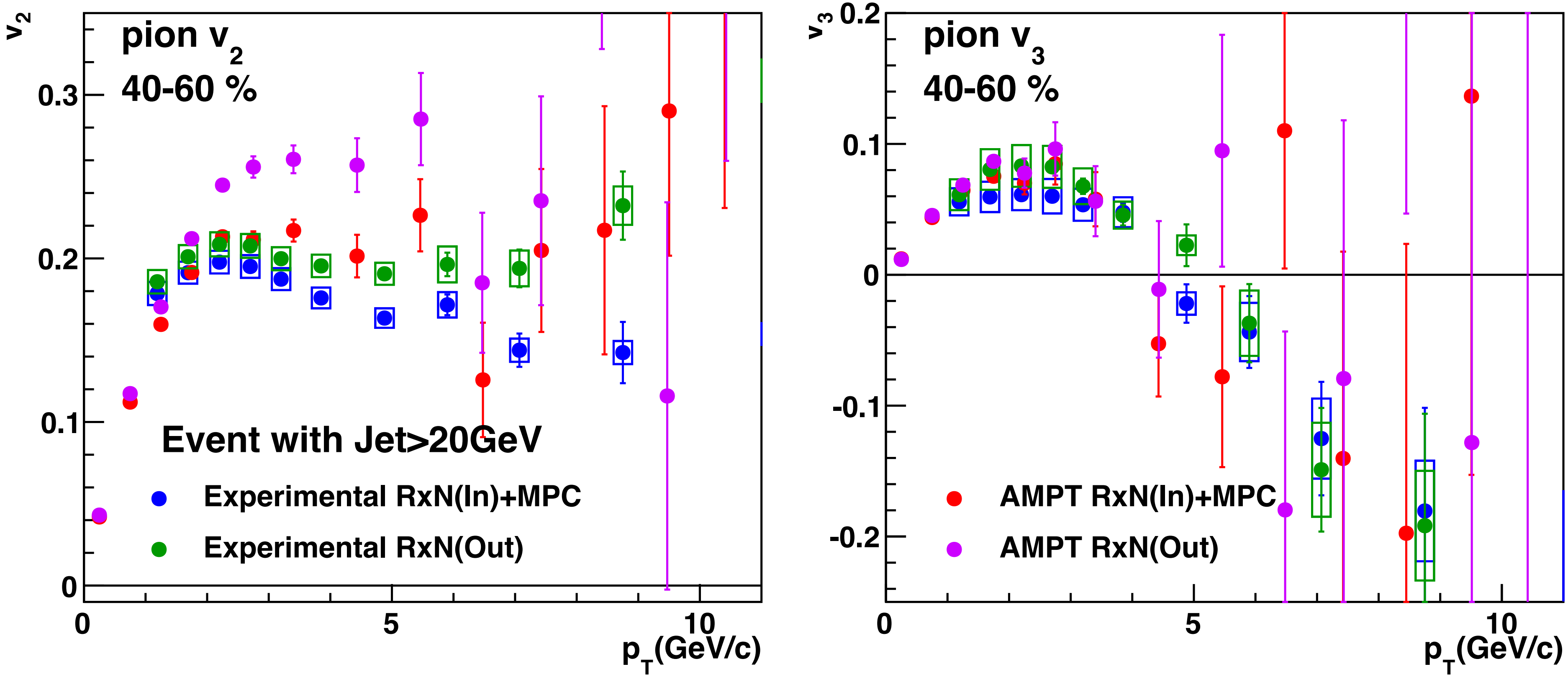
3 M events including Jet > 20 GeV are analyzed.

Centrality is defined by the number of particles in 3.1<|η|<3.9.

Pions are detected in |η|<0.35.
Event Plane is measured in
1 : 1.5<|η|<2.8 (RxN(In))
2: 1.0<|η|<1.5 (RxN(Out))
3: 1.0<|η|<2.8 (RxN(I+O))
4: 3.1<|η|<3.8 (MPC)
5: 3.1<|η|<3.9 (BBC)
6: 1.0<|η|<1.5 + 3.1<|η|<3.9 (RxN(In)+MPC)



Pion v_n simulated by AMPT

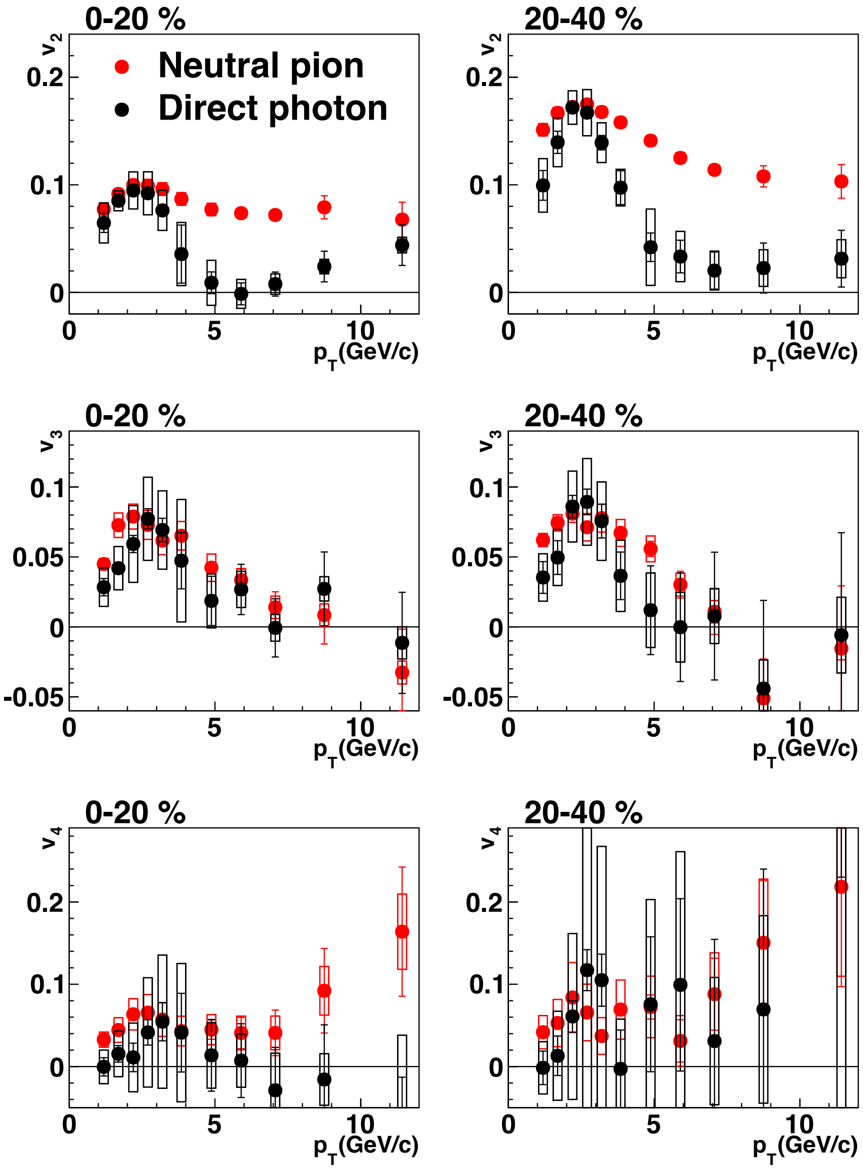


Event plane dependence is found in v_2, it is similar to the experimental measurement.

The v_3 shows similar trend less than 5 GeV/c.

Results & Discussion
Direct photon v_n

The results of neutral pion and direct photon v_n



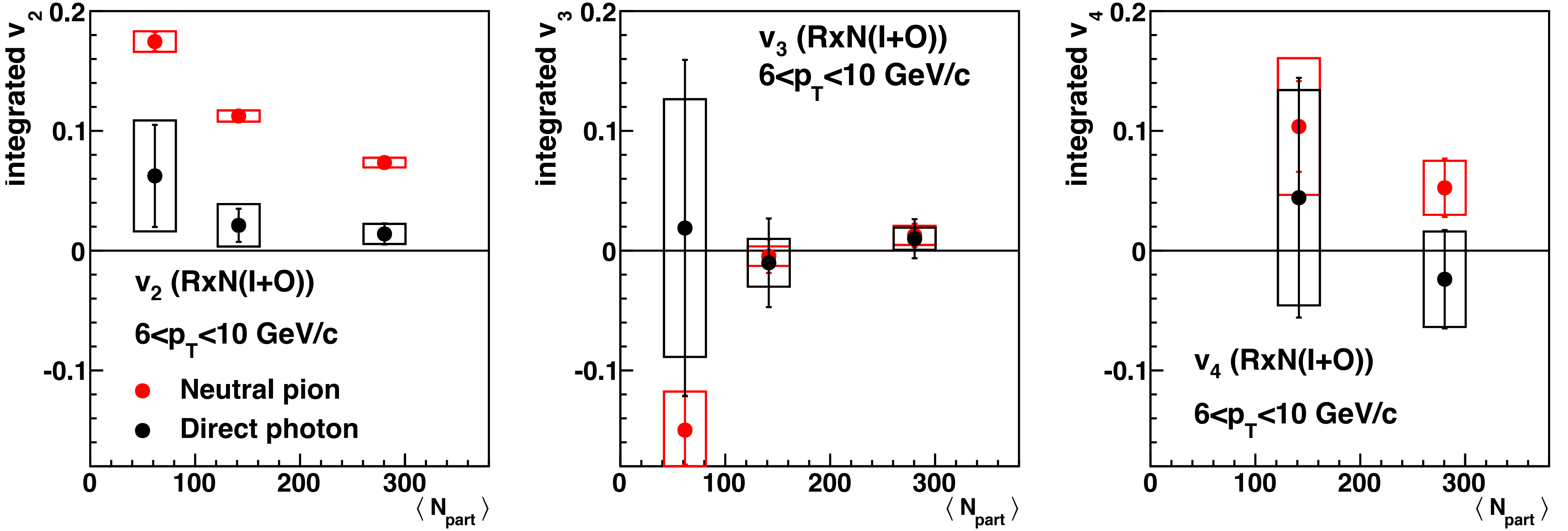
- In low p_T region

Direct photon has non-zero and positive v_2 and v_3.
The strength is comparable to the hadron v_2 and v_3.

- In high p_T region

Direct photon v_n is close to zero.

Centrality dependence of $\gamma^{dir.}$ and π^0 in high p_T



$\gamma^{dir.}$ v_2 and $v_4 < \pi^0$ v_2 and v_4
$\gamma^{dir.}$ $v_3 \approx 0$

The direct photon v_n is close to zero.
The difference between $\gamma^{dir.}$ and π^0 is understood that photon includes prompt photon which $v_n \approx 0$.

Blast wave model

Blast wave model is based on hydrodynamic model
Parameterizing the expanding medium at freeze-out temperature

p_T spectra : $$\frac{dN}{p_T dp_T} \propto \int d\phi I_0(\alpha_T) K_1(\beta_T)$$

azimuthal anisotropy : $$v_n(p_T) = \frac{\int d\phi \cos(n\phi) I_n(\alpha_T) K_1(\beta_T)\{1 + 2s_n \cos(n\phi)\}}{\int d\phi I_0(\alpha_T) K_1(\beta_T)\{1 + 2s_n \cos(n\phi)\}}$$

6 parameters
Freeze-out temperature : $\mathbf{T_f}$
average velocity : **<ρ>**
transverse anisotropy : ρ_2, ρ_3
spatial anisotropy : s_2, s_3

$$\alpha_T(\phi) = (p_T/T_f)\sinh(\rho(\phi))$$

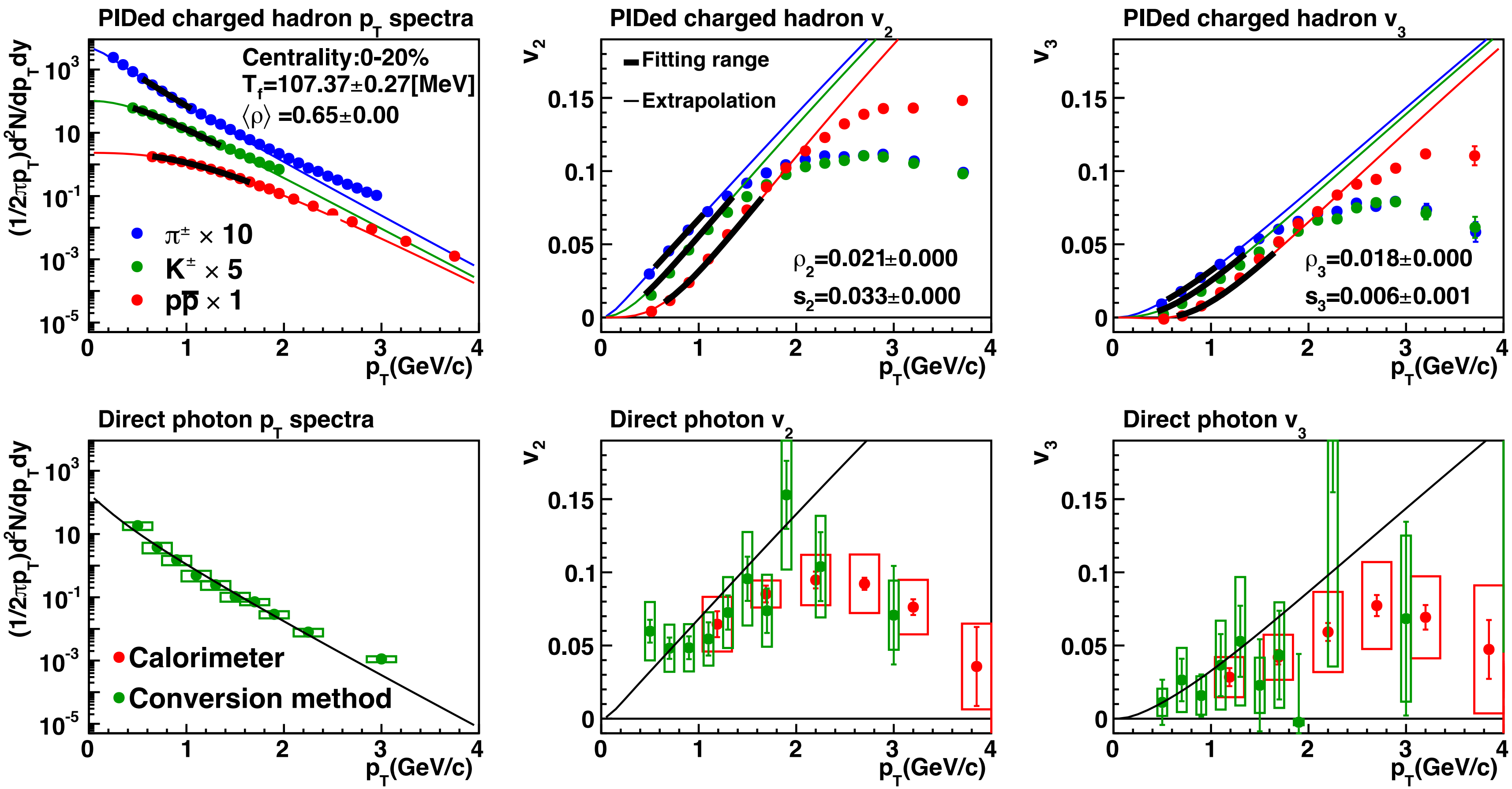
$$\beta_T(\phi) = (m_T/T_f)\cosh(\rho(\phi))$$

$$\rho(\phi) = \rho_0(1 + 2\rho_n \cos(n\phi))$$

$$\langle\rho\rangle = \frac{\int r(\rho_0 \times r/R_{max})dr}{\int r\ dr}$$

6 parameters are defined by hadron observables.
Photon spectra and v_n are predicted as massless particle (mass = 0).

Photon observables predicted blast wave model



Photon observables are well described with parameters defined from hadron.
The p_T spectra is described though temperature is very low ($T_{eff.}$ =240 MeV).
It could be due to strong radial flow (like blue shift correction).

The probability of understanding photon puzzle

Blast wave model well describes photon p_T spectra and v_n at freeze-out temperature ($T_{FO} \approx 100$ MeV).
Effective temperature could be affected by strong radial flow.

The possibility that photons from early stage are not dominant.

Photon p_T spectra and v_n are calculated with blue shift effect.

$$T' = T\sqrt{\frac{1+\beta}{1-\beta}}$$

T' : apparent temperature
β : velocity of photon source
$T < T'$

Photon p_T spectra and v_n with blue shift effect

Assumption of photon source

- temperature decreases with the time : T(t)
- velocity increases with the time : $\beta(t)$
- azimuthal anisotropy increases with the time $v_n(p_T, t)$
- thermal photon momentum distribution :

$$n(p_T, t) = \frac{p_T}{\exp\left(p_T/T(t)\right) - 1}$$

p_T spectra and v_n at final state are calculated as :

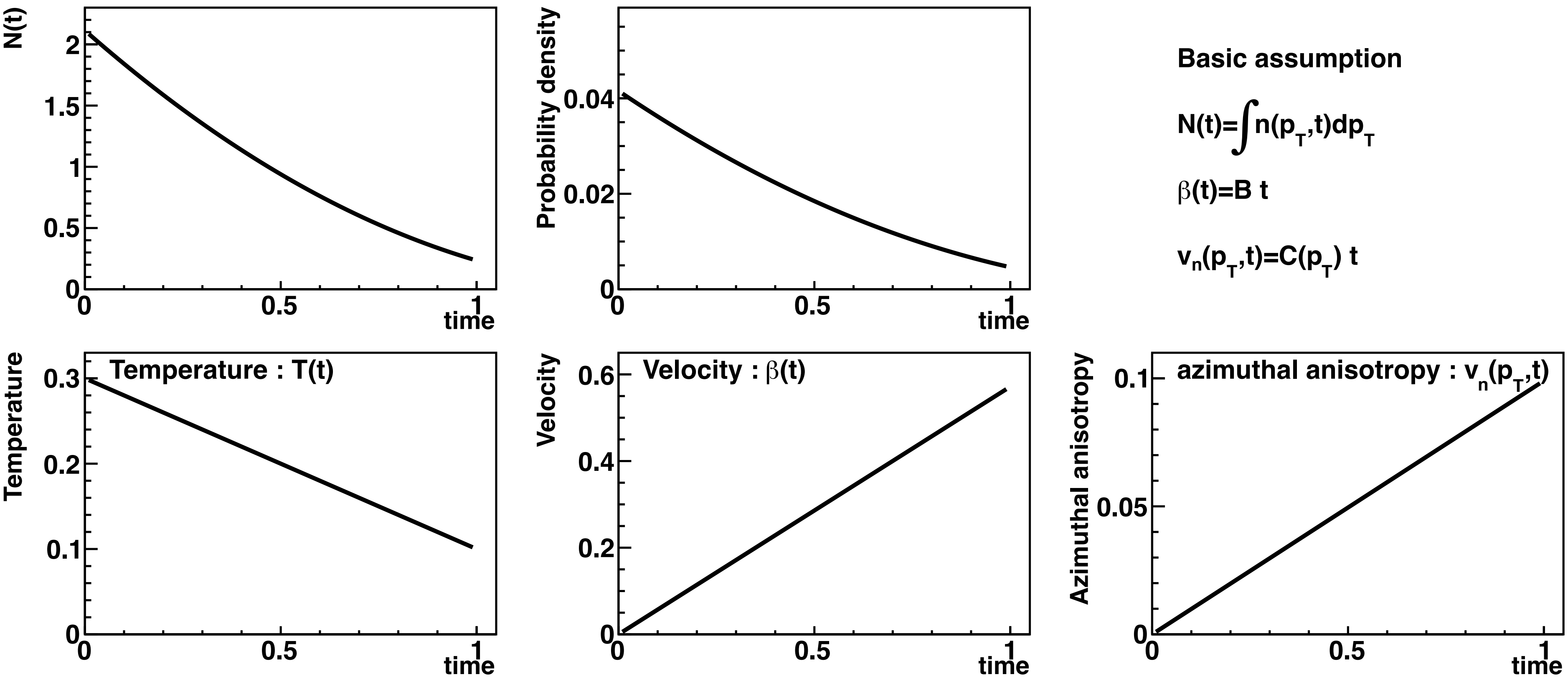
$$n^{\text{fin.}}(p_T) = \int dtn(p_T, t) \qquad v_n^{\text{fin.}}(p_T) = \frac{\int dtn(p_T, t)v_n(p_T, t)}{\int dtn(p_T, t)}$$

Effective temperature is taken via fitting by exponential equation to p_T spectra.
The difference with experimental measurement is estimated as :

$$(V_{\text{obs.}} - V_{\text{cal.}})/E(\text{stat.} \oplus \text{sys.})$$

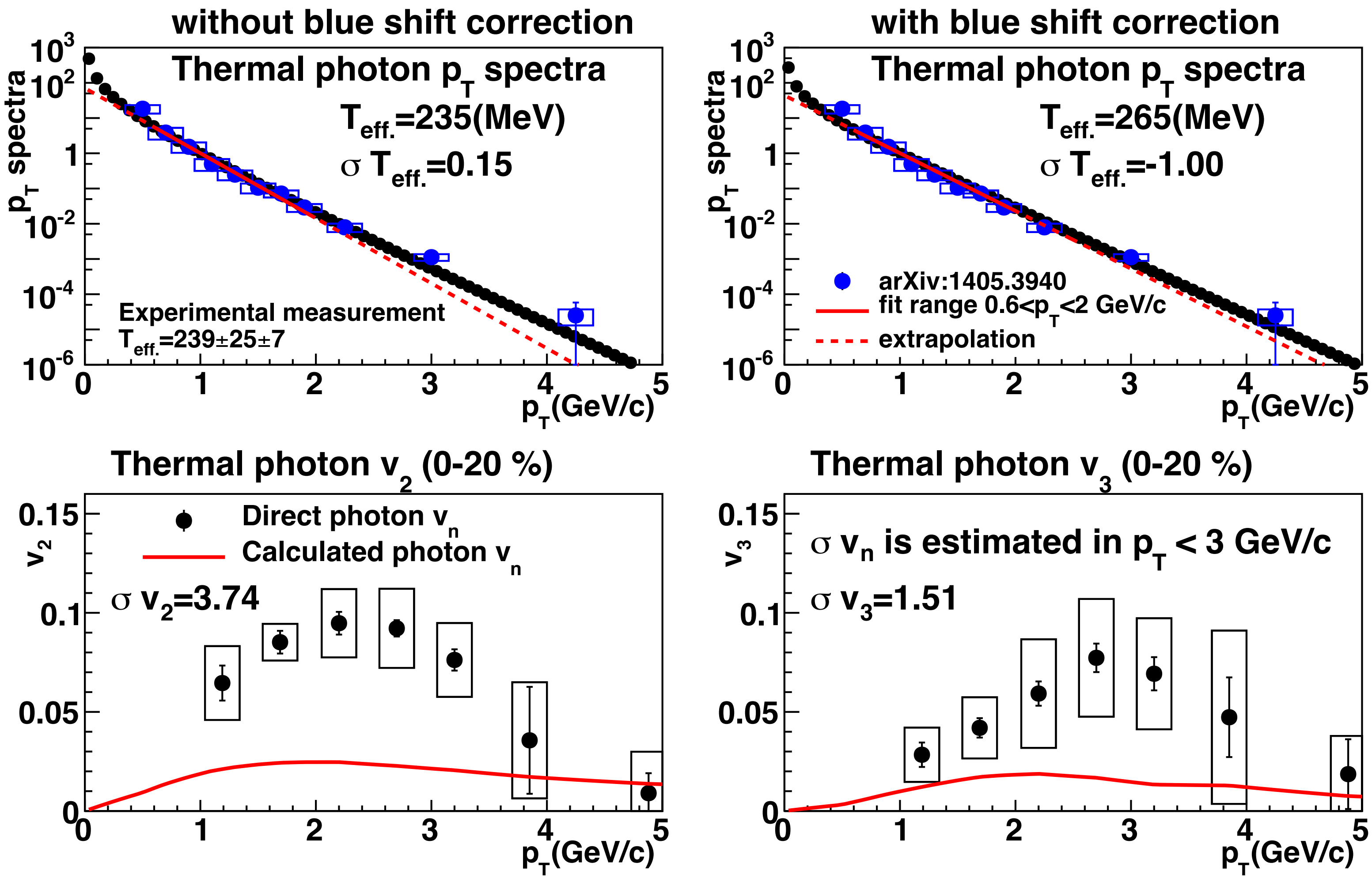
$V_{obs.}$: experimental measurement
E : error of $V_{obs.}$
$V_{cal.}$: calculation

Basic assumption for yield, velocity, and anisotropy



The temperature is decreased from 300 MeV to 100 MeV.
The time is defined by temperature.

Calculation with basic assumption



Effective temperature with blue shift is higher than without correction.
The v_n are much underestimated.

Additional assumption

- **Yield dependence**

Since photon source expands, the yield is assumed to get large with time.

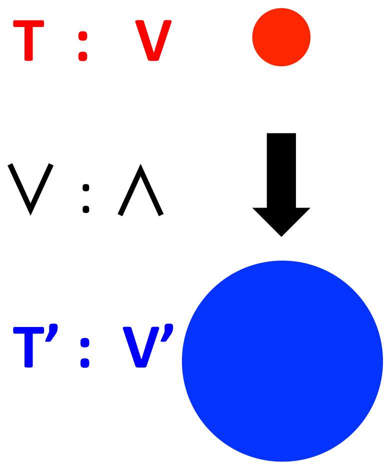
$$N(t) = \int dp_T t^a n(p_T, t)$$

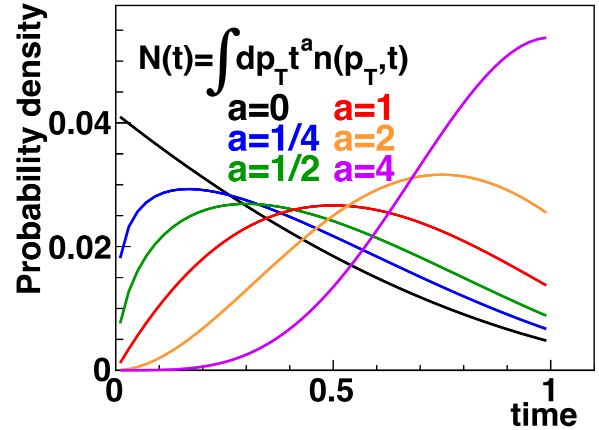
- **Velocity dependence**

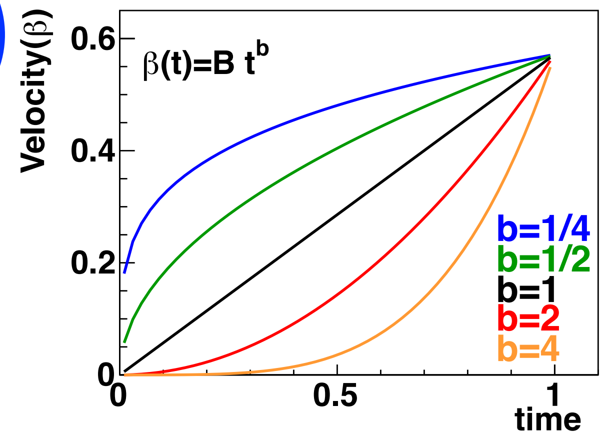
$$\beta(t) = B \cdot t^b$$

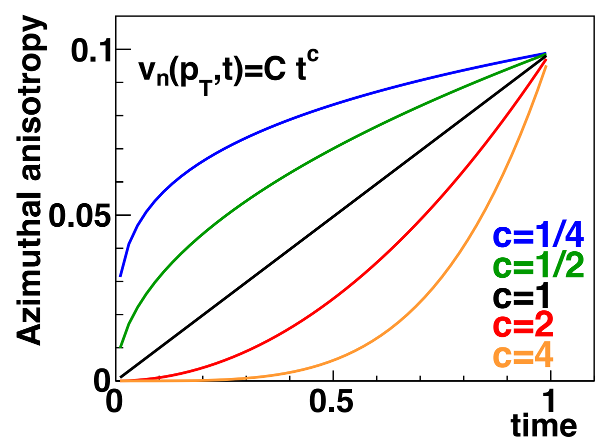
- **Azimuthal anisotropy dependence**

$$v_n(p_T, t) = C(p_T) \cdot t^c$$



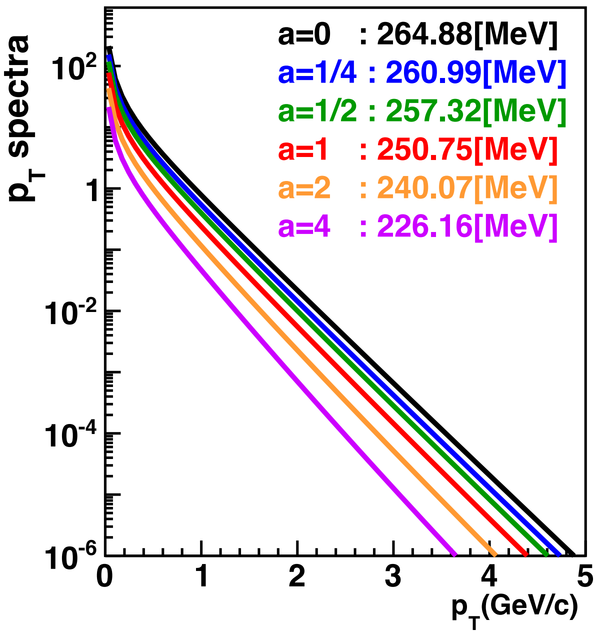


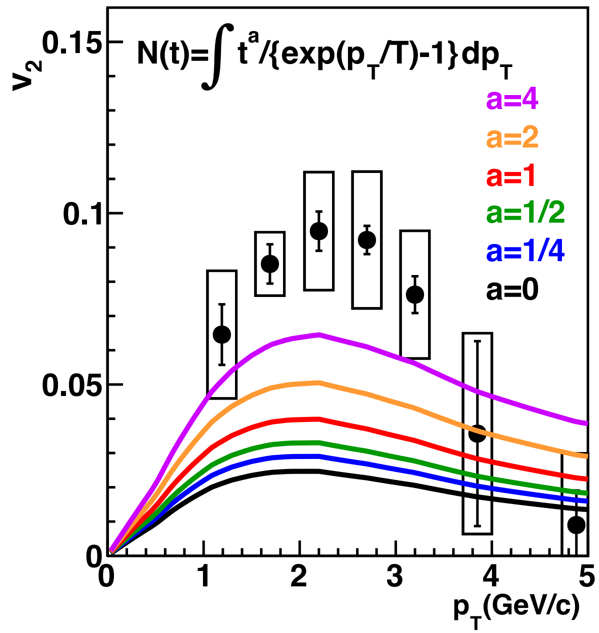


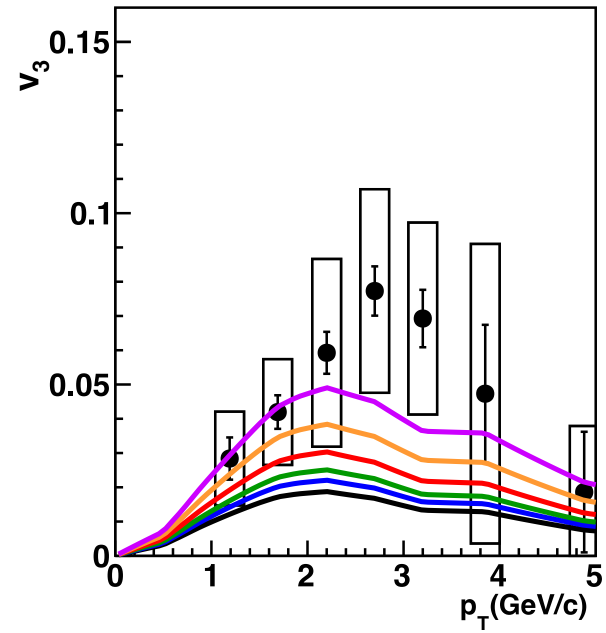


p_T spectra and v_n with relative yield dependence

$$N(t) = \int dp_T t^a n(p_T, t)$$

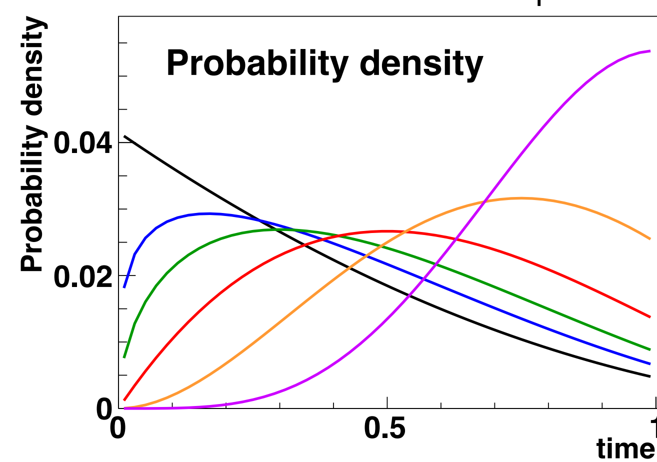






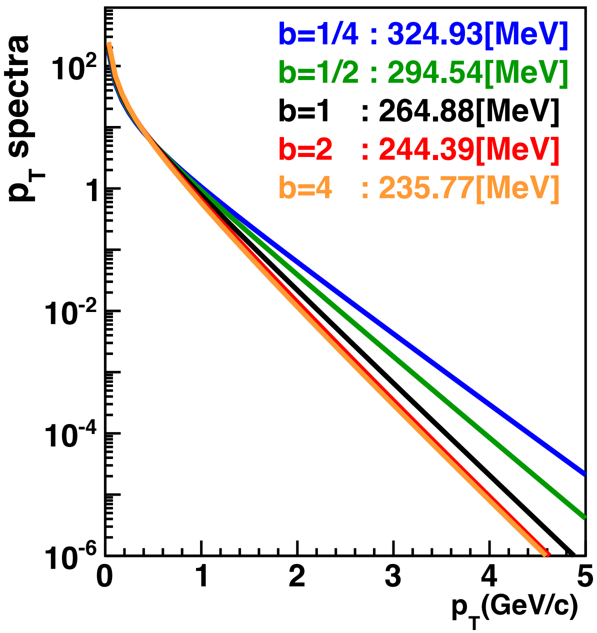
Photons from late stage :
low temperature & large v_n

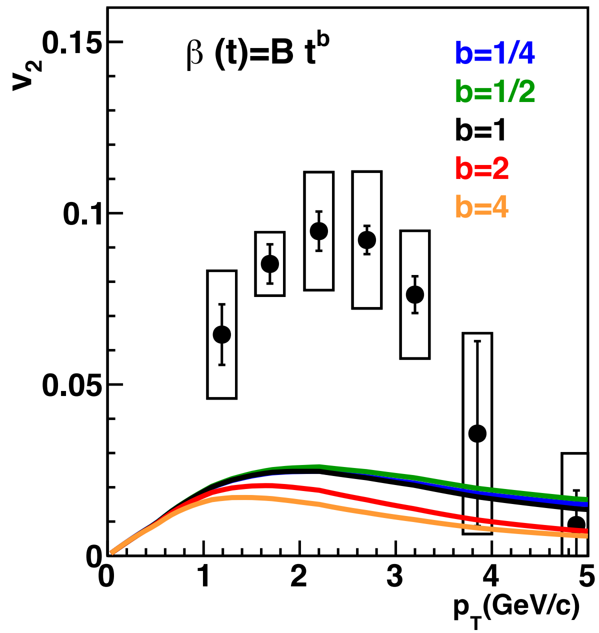
The both of effective temperature
and v_n are affected.

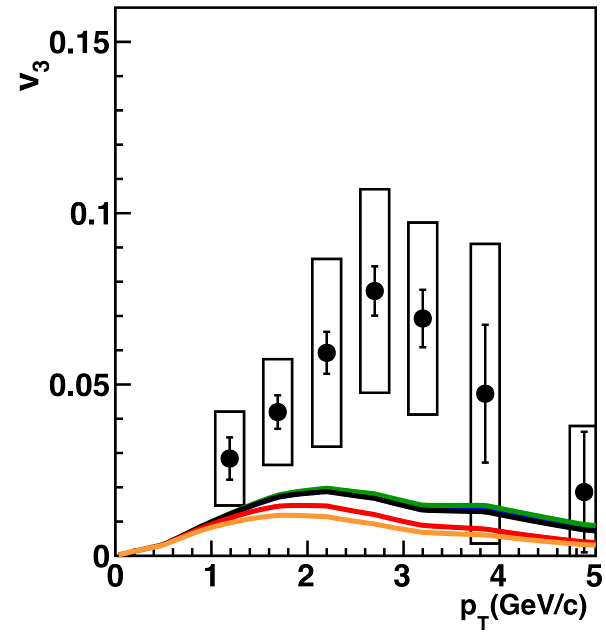


p_T spectra and v_n with velocity dependence

$$\beta(t) = B \cdot t^b$$

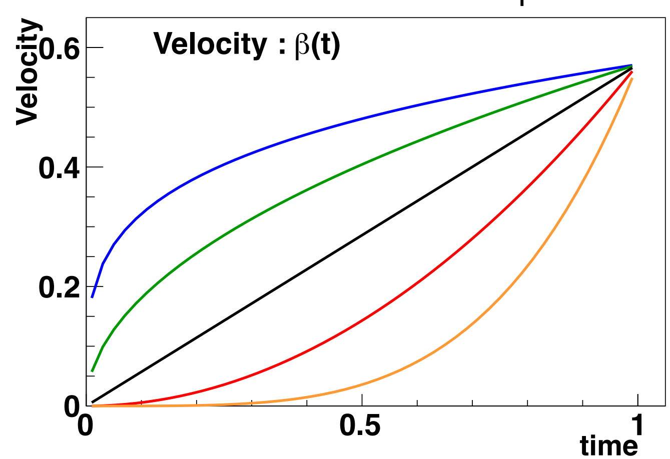






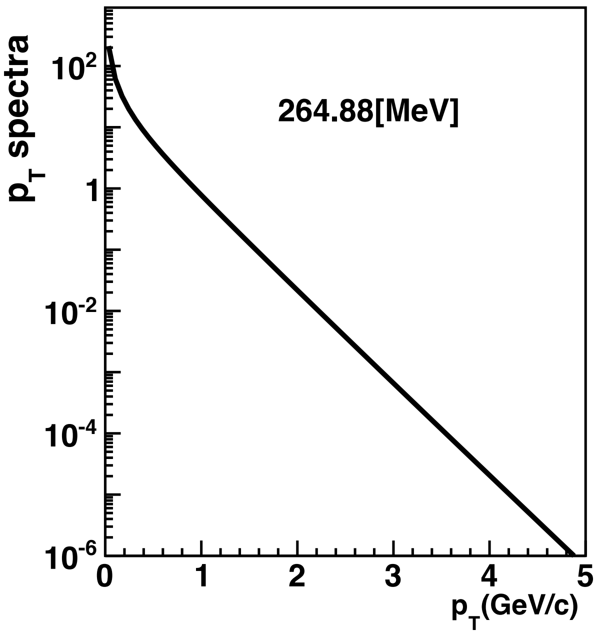
Effective temperature significantly decreases with increasing “b”.

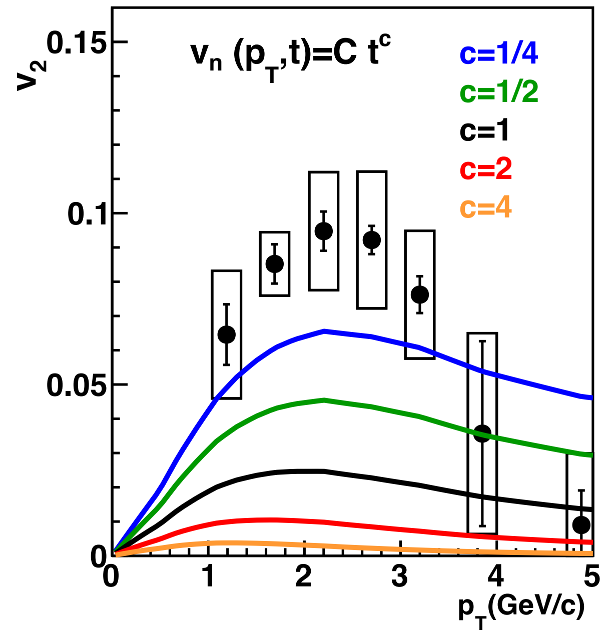
The v_n is a slightly affected.

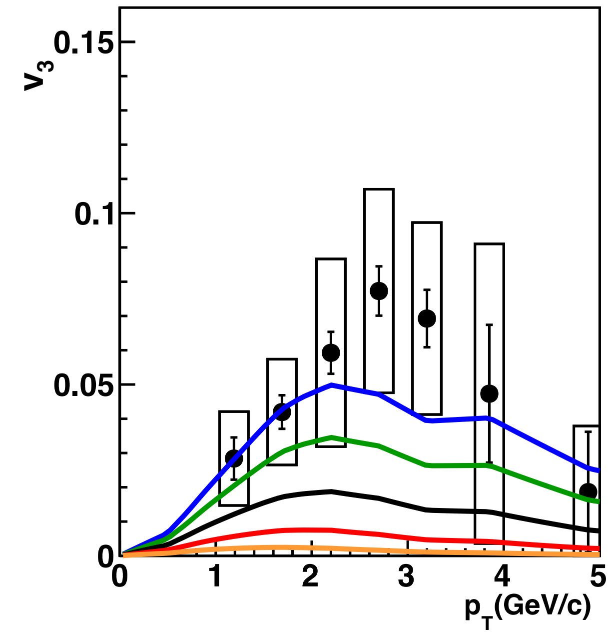


p_T spectra and v_n with anisotropy dependence

$$v_n(p_T, t) = C(p_T) \cdot t^c$$

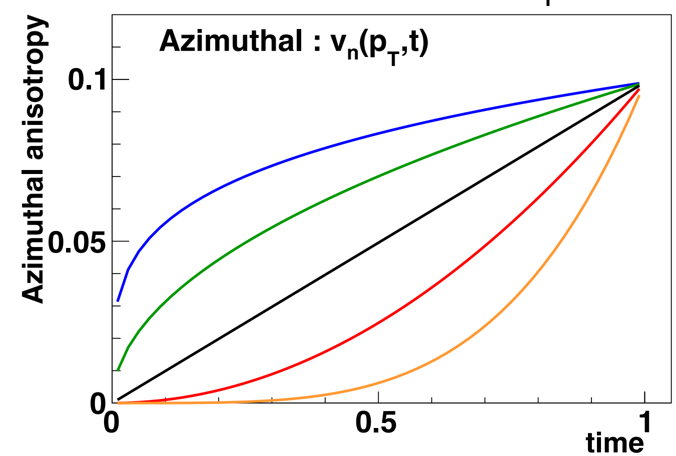




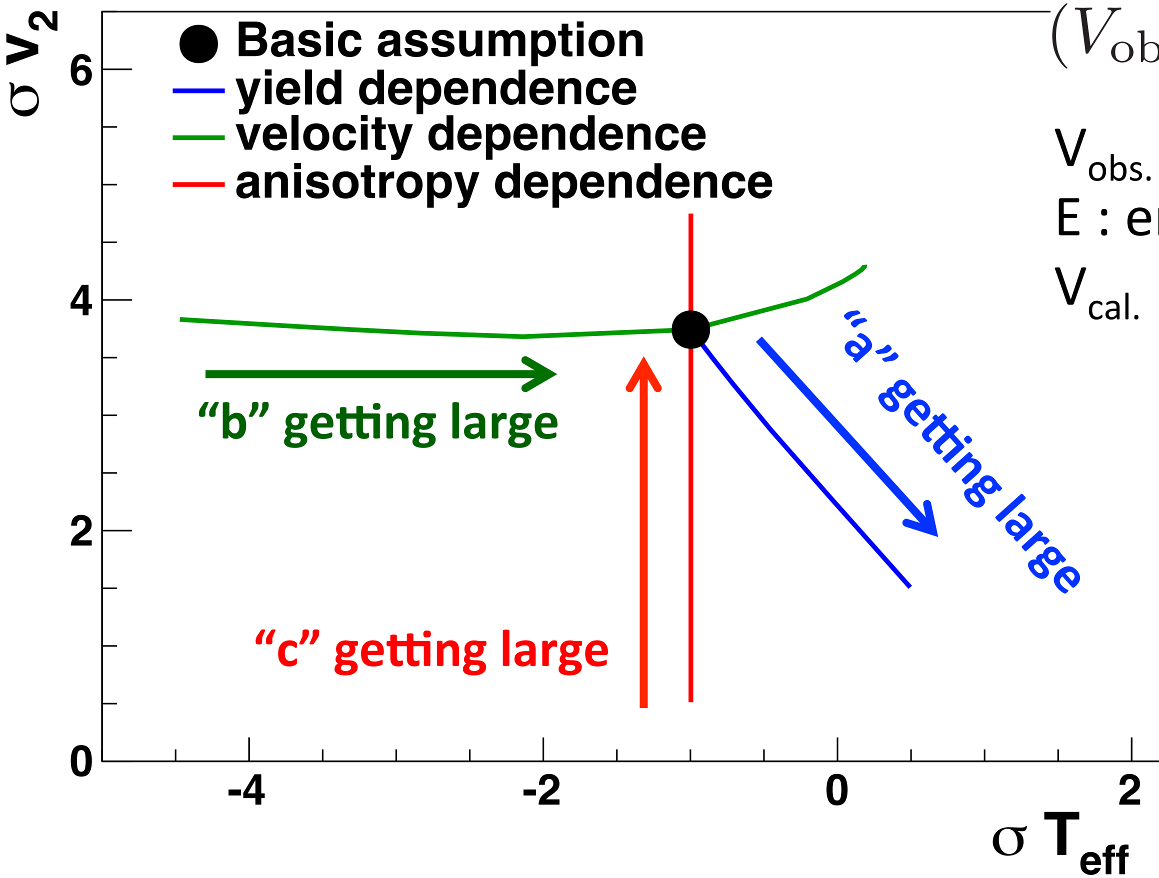


Since p_T spectra is not affected, effective temperature is not varied.

The v_n increases with “c” decreasing.



Comparison with experimental measurement



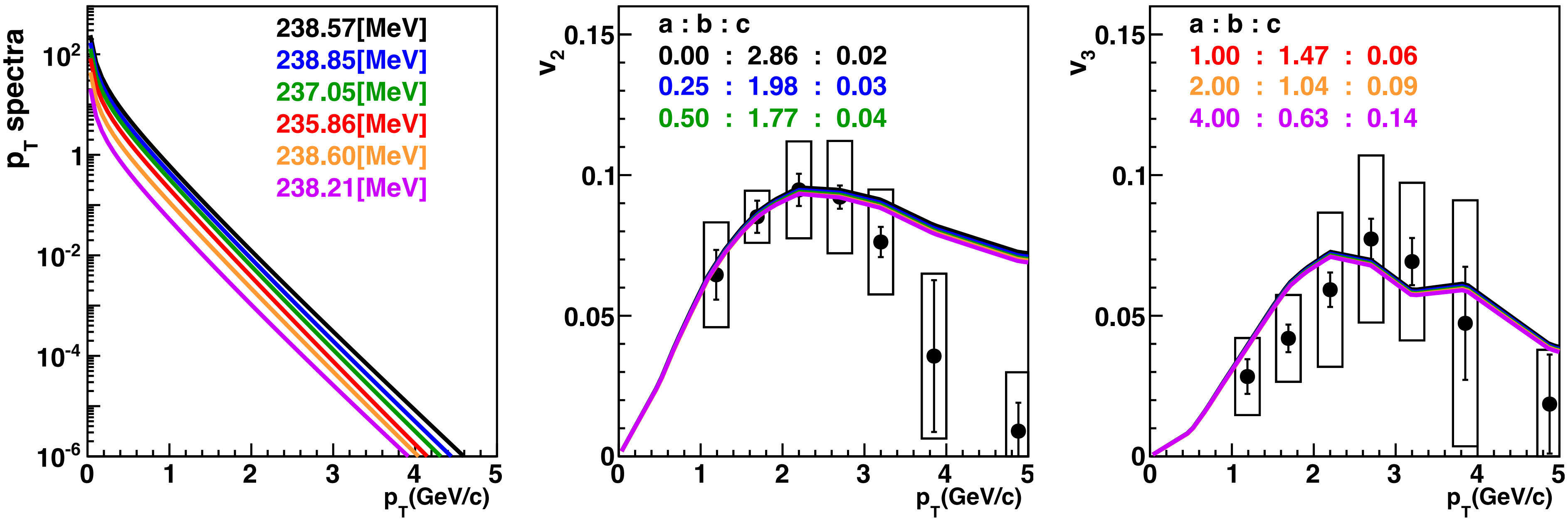
$$(V_{\text{obs.}} - V_{\text{cal.}})/E(\text{stat.} \oplus \text{sys.})$$

$V_{obs.}$: experimental measurement
E : error of $V_{obs.}$
$V_{cal.}$: calculation result

$$N(t) = \int dp_T t^a n(p_T, t)$$
$$\beta(t) = B \cdot t^b$$
$$v_n(p_T, t) = C(p_T) \cdot t^c$$

The differences (σT_{eff} and σv_2) are varies uniquely with the parameters "a", "b", and "c".
They are selected so that $T_{eff.}$ and v_2 are comparable to the experimental measurement.

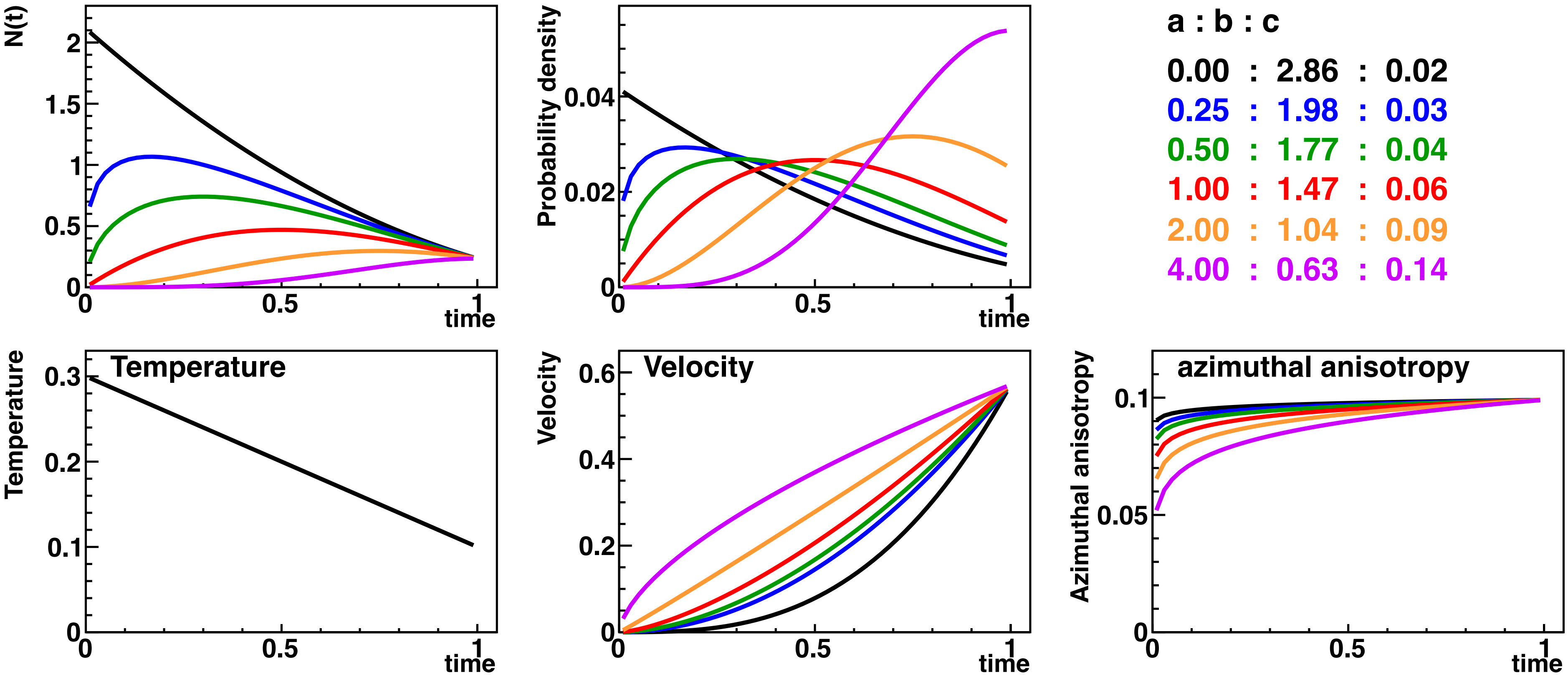
p_T spectra and v_n with selected parameters



Parameter "b" is selected so that effective temperature is comparable to experimental measurement.

The "c" is chosen to be comparable to v_2.

Selected dependence of velocity and anisotropy



The development of velocity and v_n could be studied.
The time dependence of v_n of medium shows that v_n is saturated early.

Summary (1)

Neutral pion and direct photon v_n are measured in $\sqrt{s_{NN}}$ = 200GeV Au+Au collisions at RHIC-PHENIX experiment.

Neutral pion v_2, v_3, and v_4 show different pattern in high p_T region.
In central collisions, hadron shows non-zero v_n.
    It could be understood that jet path-length dependence.
In peripheral collisions, v_2 & v_4 have positive while v_3 shows negative.
    It could be due to jet effect on determining event plane.

Comparison of neutral pion and direct photon in high p_T region.
Hadron shows non-zero while photon v_n is close to zero.
It could be understood that photon includes prompt photons with $v_n \approx 0$.

Summary (2)

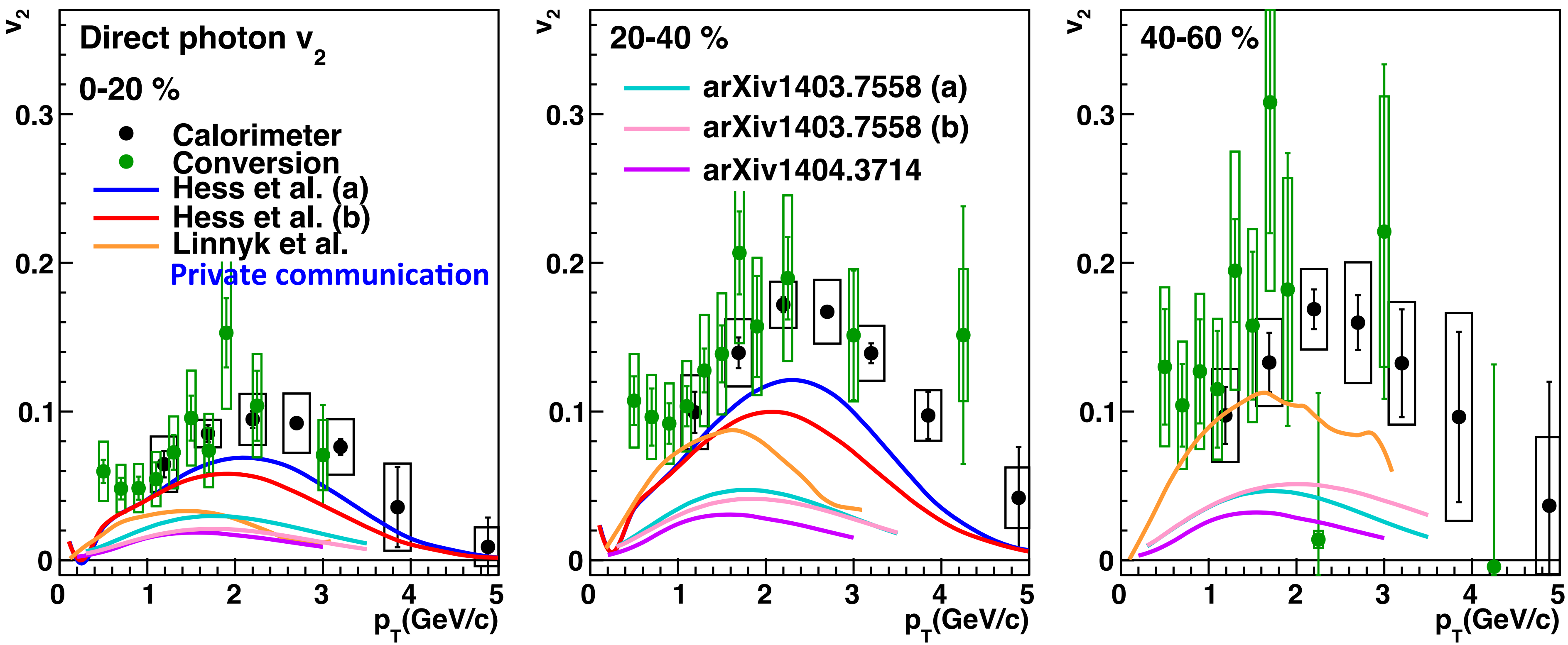
Strong radial flow effect could be the probability of explanation "photon puzzle".
High effective temperature could be understood that photon emitted from the medium having large radial velocity at late stage.

Photon p_T spectra and v_n are calculated with blue shift effect.

The time dependences are selected so that effective temperature and v_2 are comparable to the experimental measurement.
It is found that the medium azimuthal anisotropy is saturated early time of development.

Model comparison of photon v_2

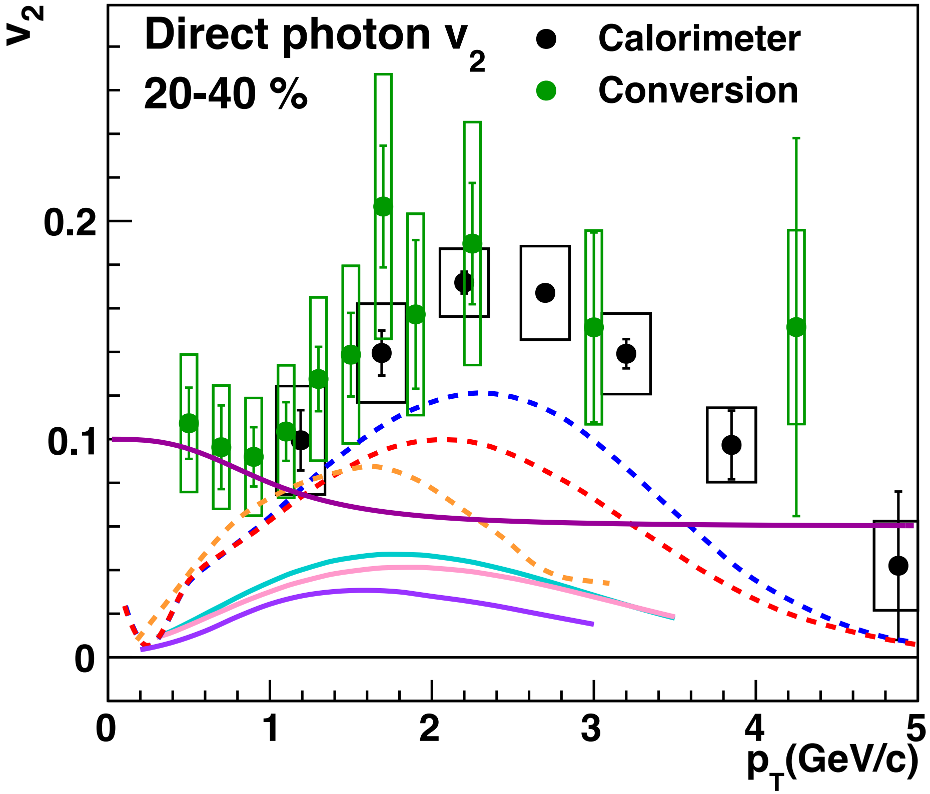
PRC 84,054906
PRC 89,034908

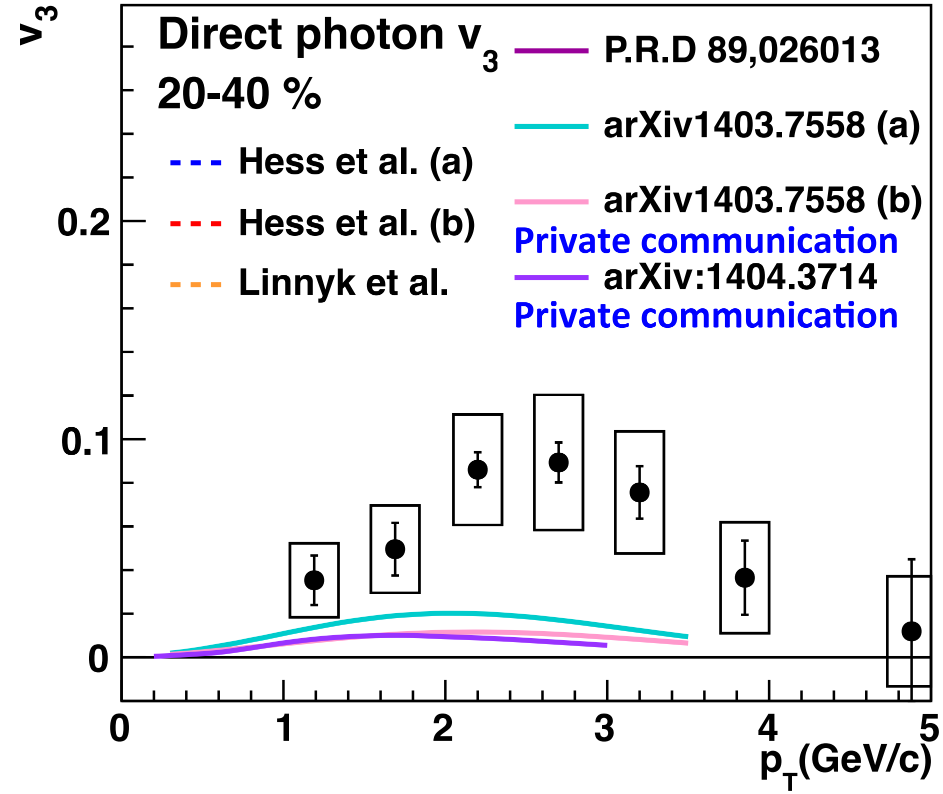


(Orange) Transport model considering photons from hadron phase
(Blue, red) Fireball model
Hydrodynamic calculations (cyan, pink, and violet) including photons from late state, are much underestimated.

Model comparison of v_2 and v_3

PRC 84,054906
PRC 89,034908
P.R.D 89,026013
arXiv:1404.3714

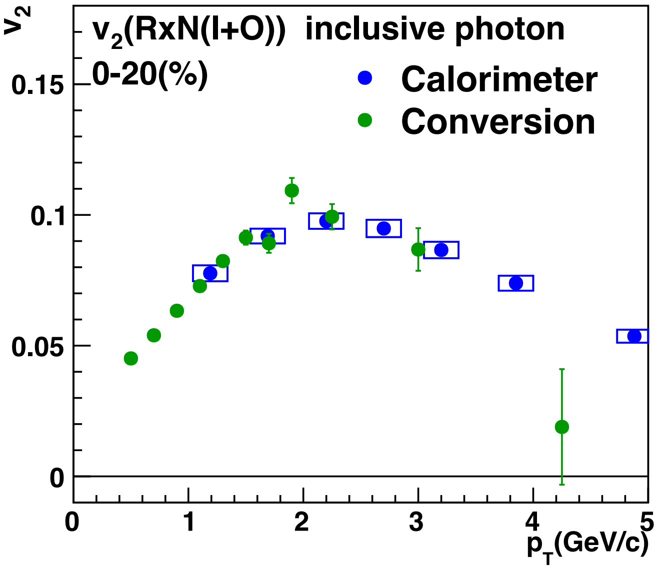


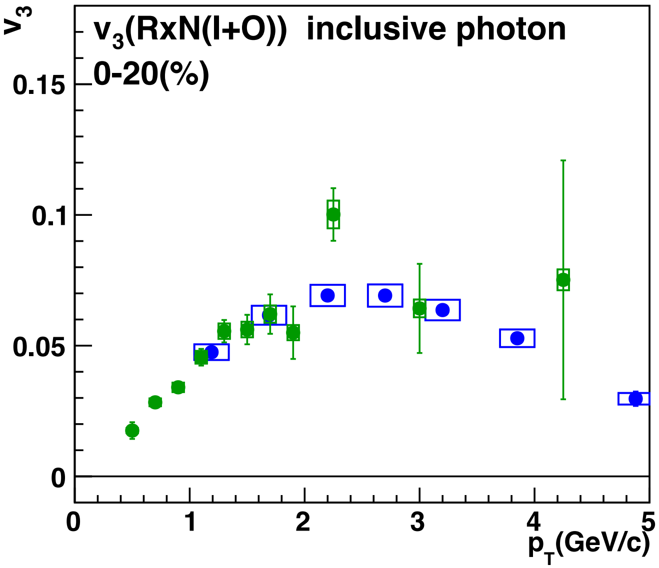


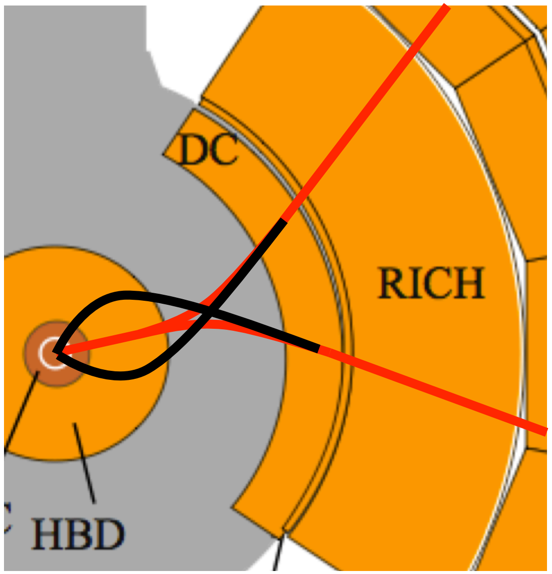
Dark violet is based on magnetic field effect, upper limit is shown.
Model calculations of photon v_3 are much smaller than experimental data.
The data of v_3 may help to constrain parameters in model calculations.

External photon conversion method

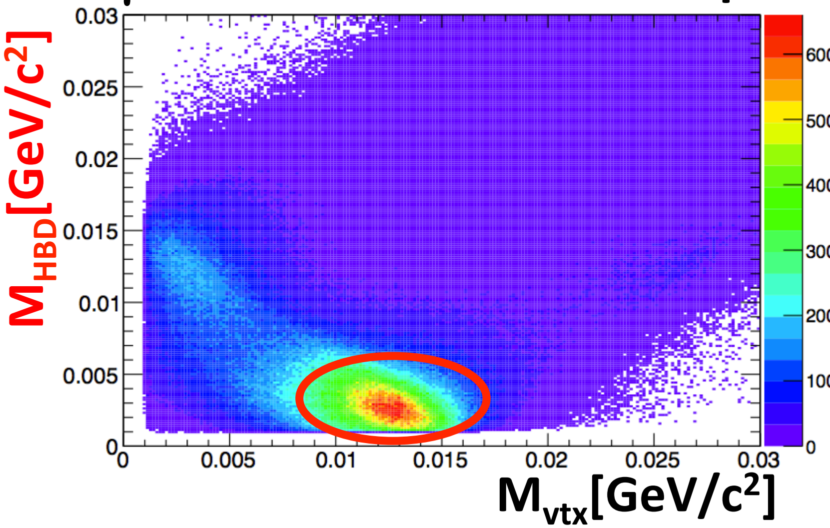
M_{HBD}: Real track
M_{vtx} : Measured track







γ Invariant mass of e^++e^- pair



Real photons from **external photon conversion** at the Hadron Blind Detector (HBD) readout plane are detected.

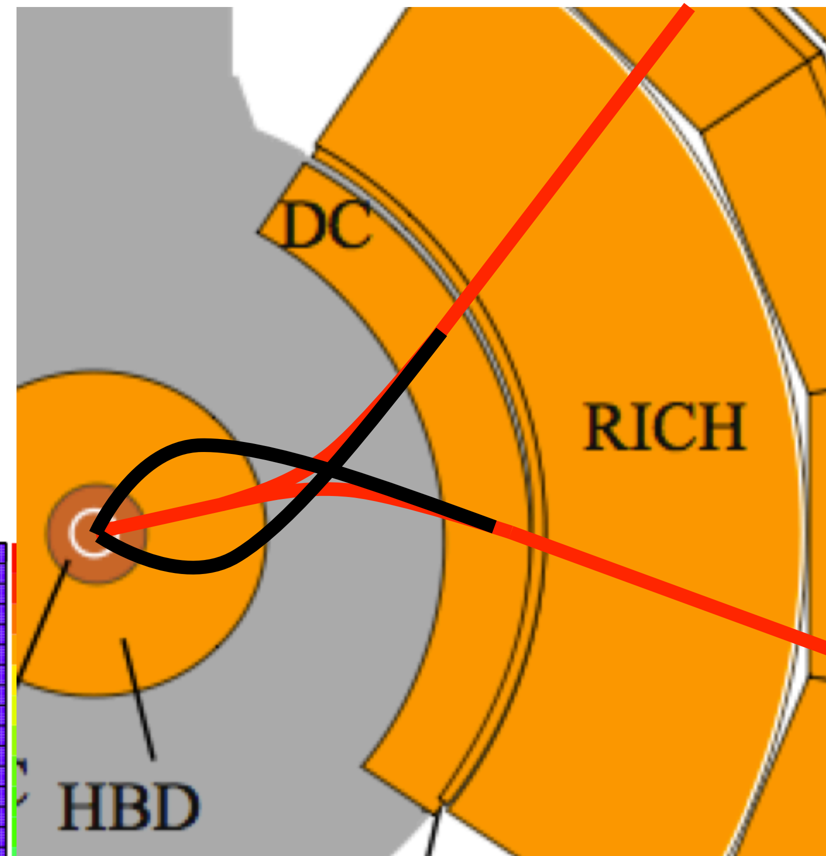
- Extend low p_T limit

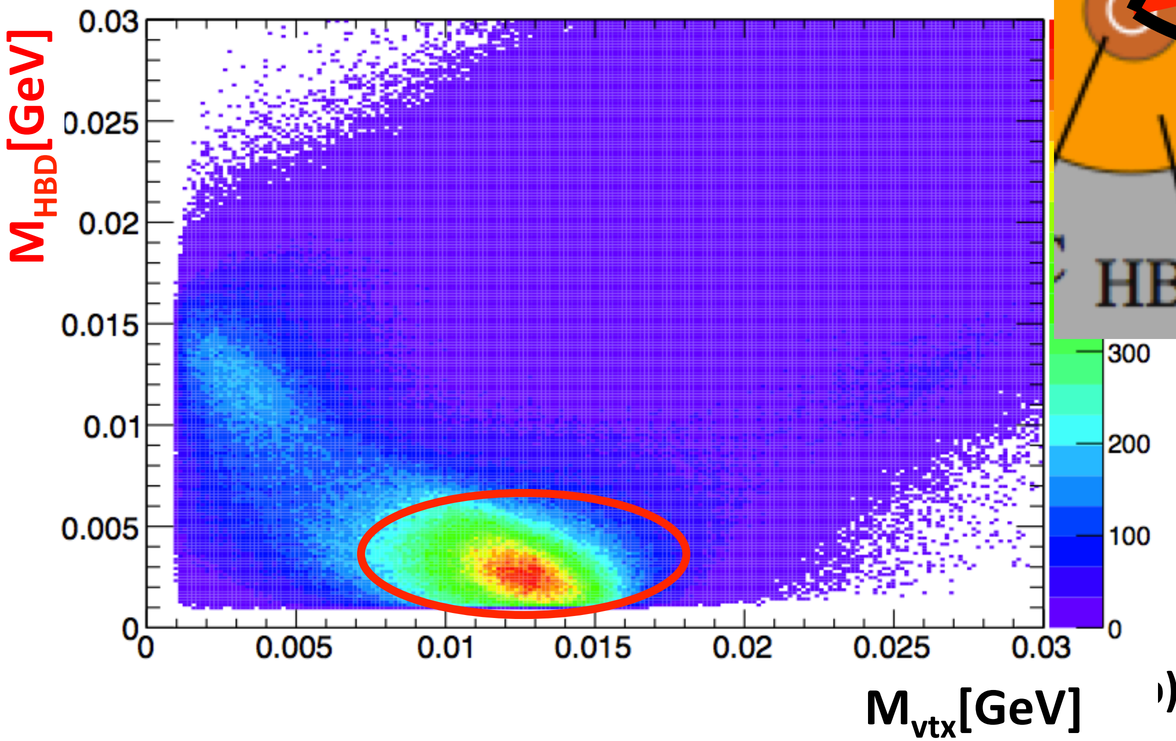
Consistent inclusive photon v_n well

External photon conversion method

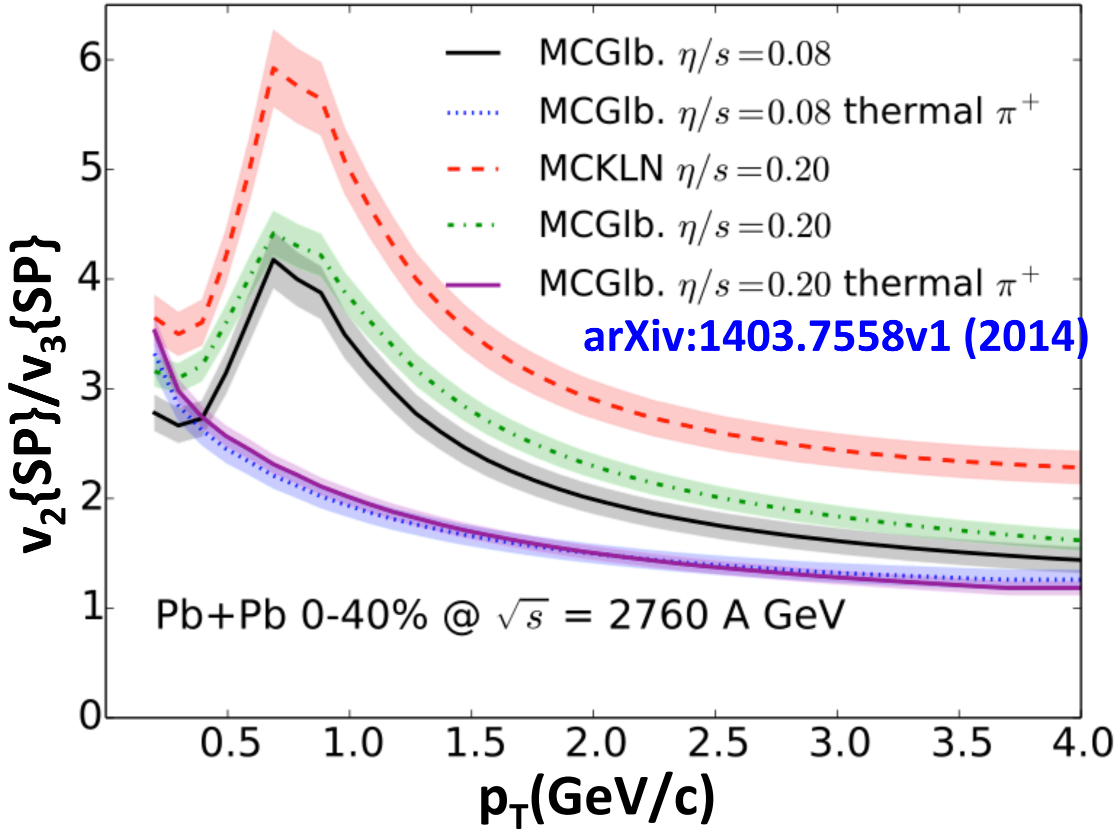
1) real photon converts to e^+e^- in HBD backplane
2) default assumption: track come from the vertex
3) momentum of the conversion tracks will be mis-measured (see black tracks)
4) apparent pair-mass (about 12MeV) will be measured for phtons
5) assume the same tracks originate in the HBD backplane
6) re-calculate momentum and pair mass with this "alternate tracking model"
7) for true converted photons M_{atm} will be around zero

Real track
estimated track





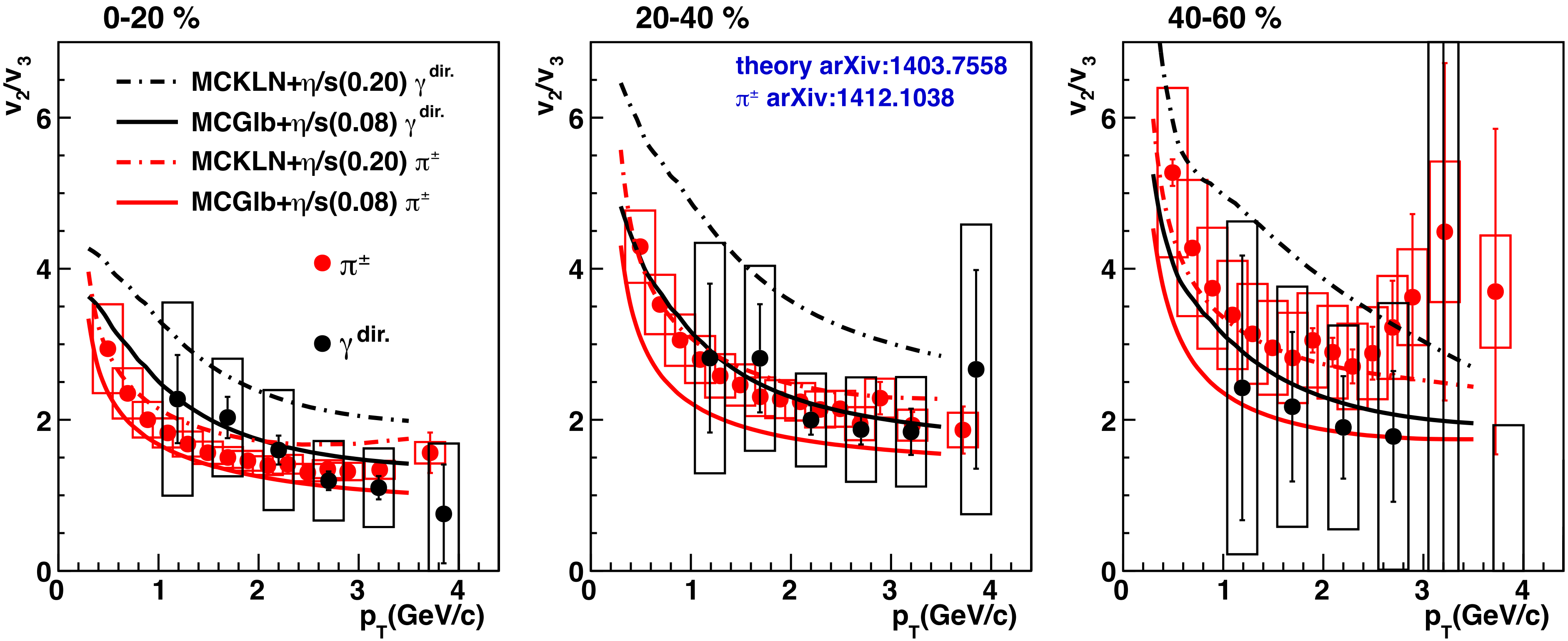
Thermal photons are predicted sensitive to η/s



Hydrodynamic calculation predicts that direct photon is sensitive to η/s of QGP than hadron.

The ratio of v_2 to v_3 in p_T region

$\pi^{\pm}$: arXiv:1412:1038
Model : arXiv:1403.7558
Private communication

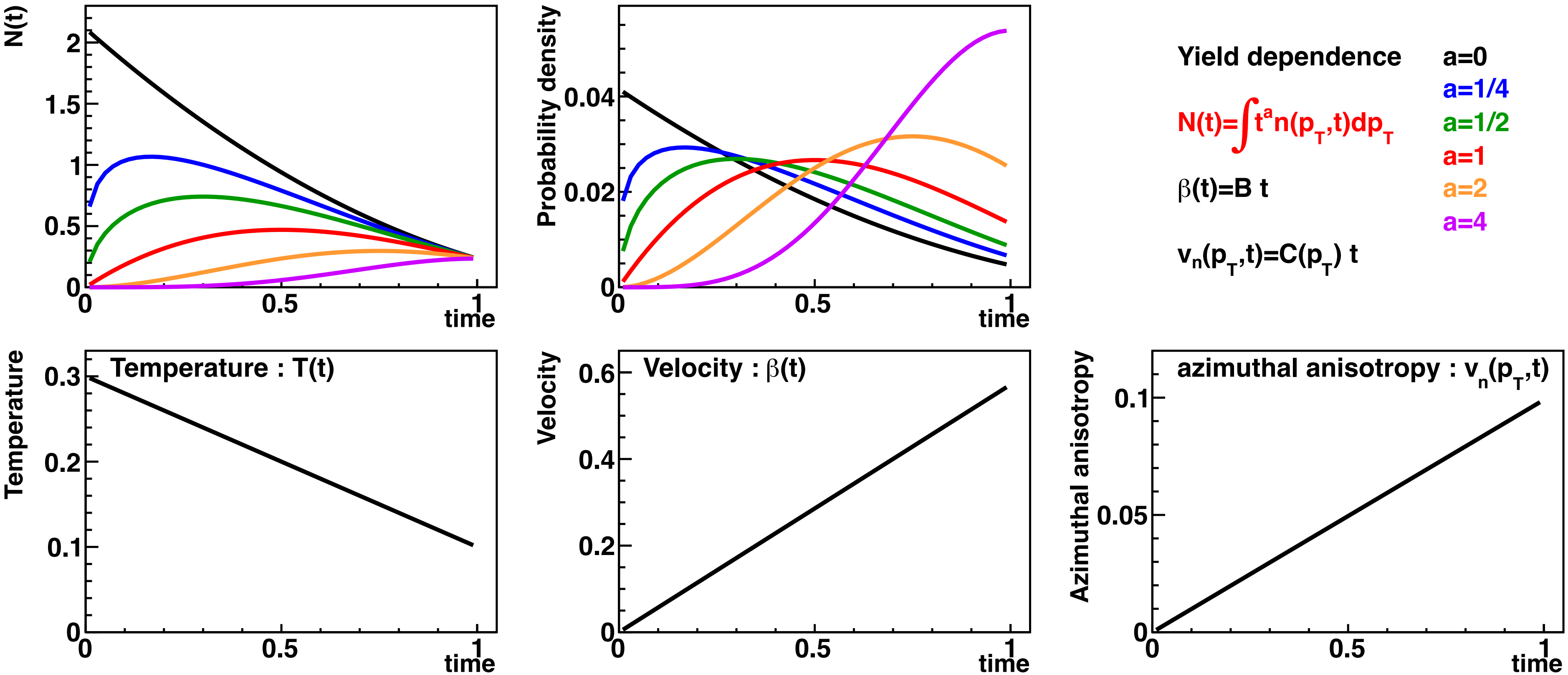


- Photons don't have strong centrality dependence at around 2-3 GeV/c
- Pions increase from central to peripheral

Photon and pion show different centrality dependence.

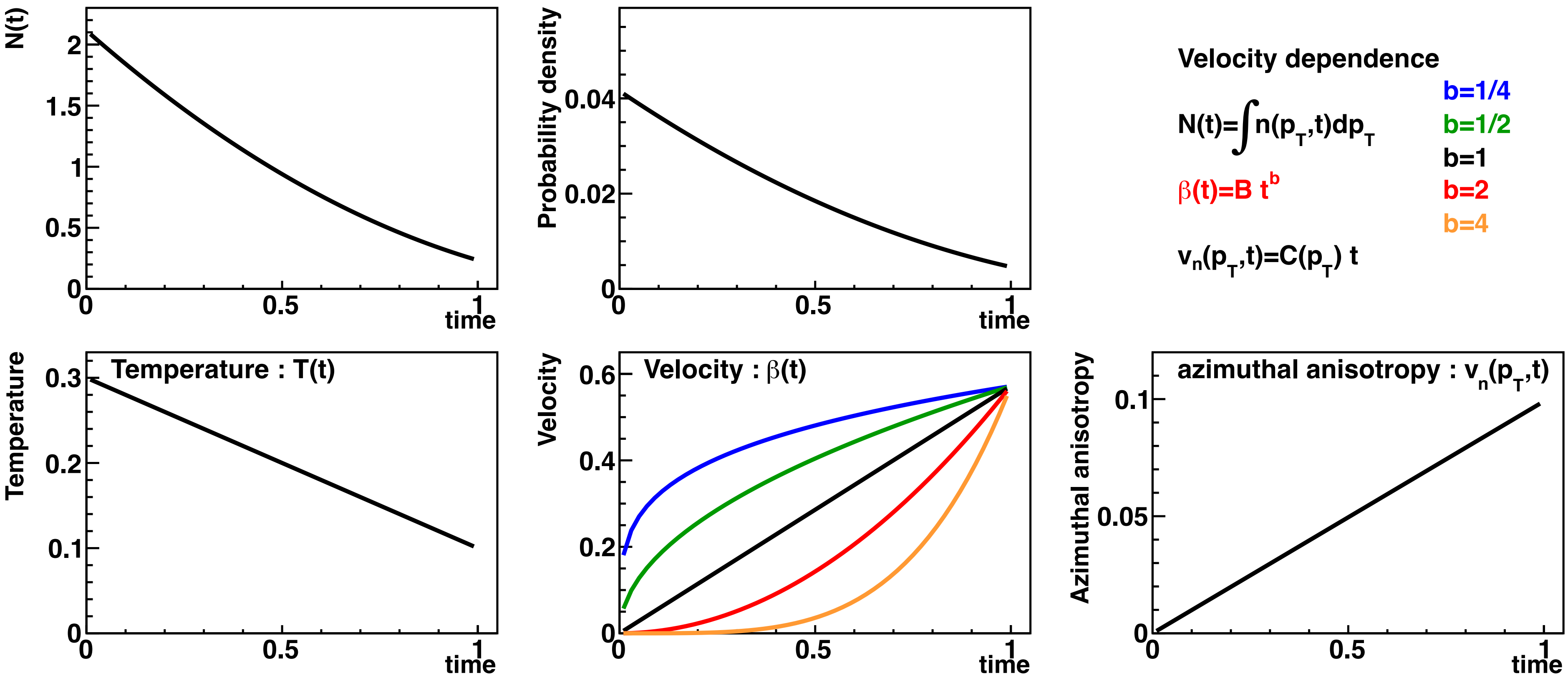
Relative yield dependence

$$N(t) = \int t^a n(p_T, t) dp_T$$



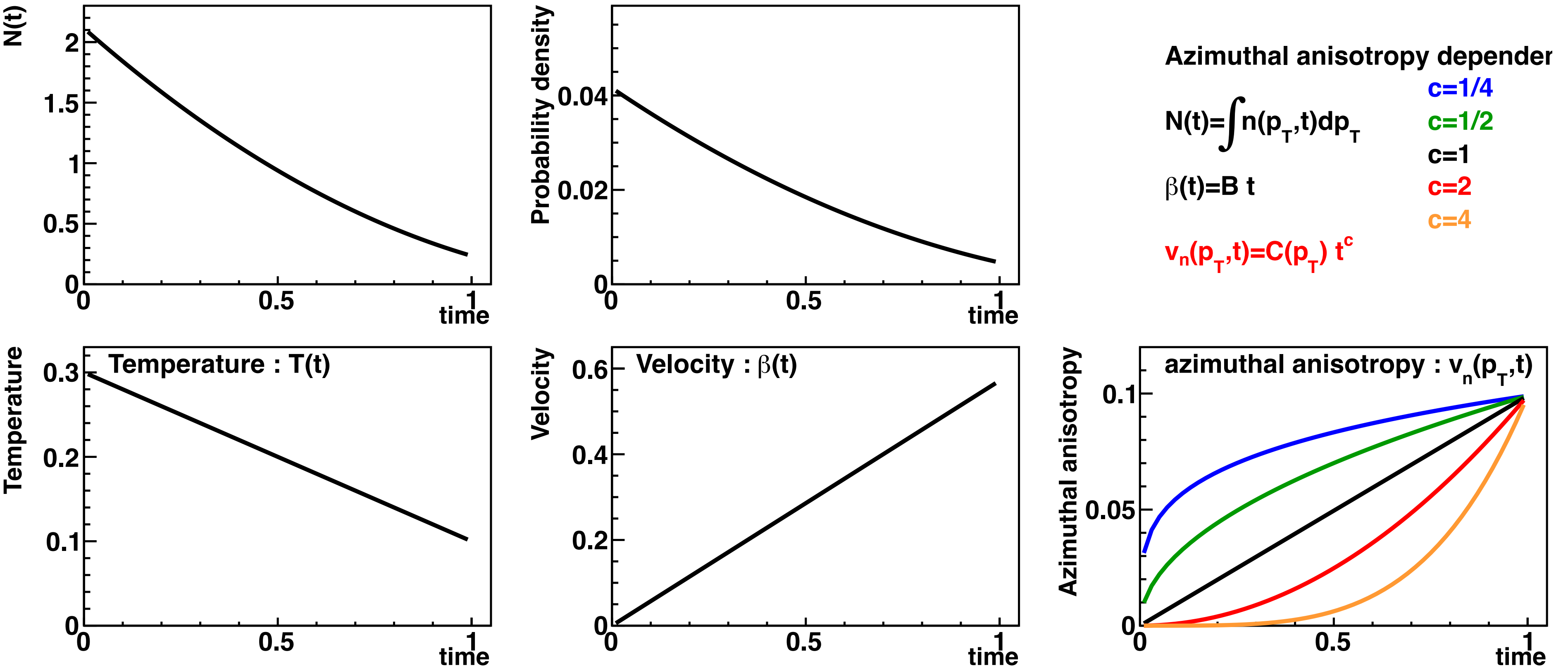
Relative probability density is modified.

The velocity dependence

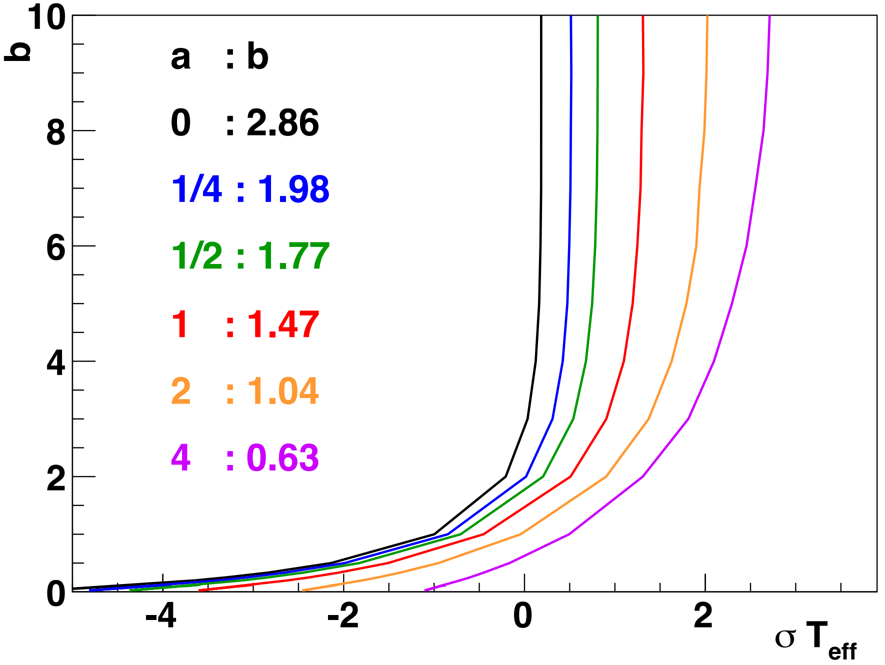


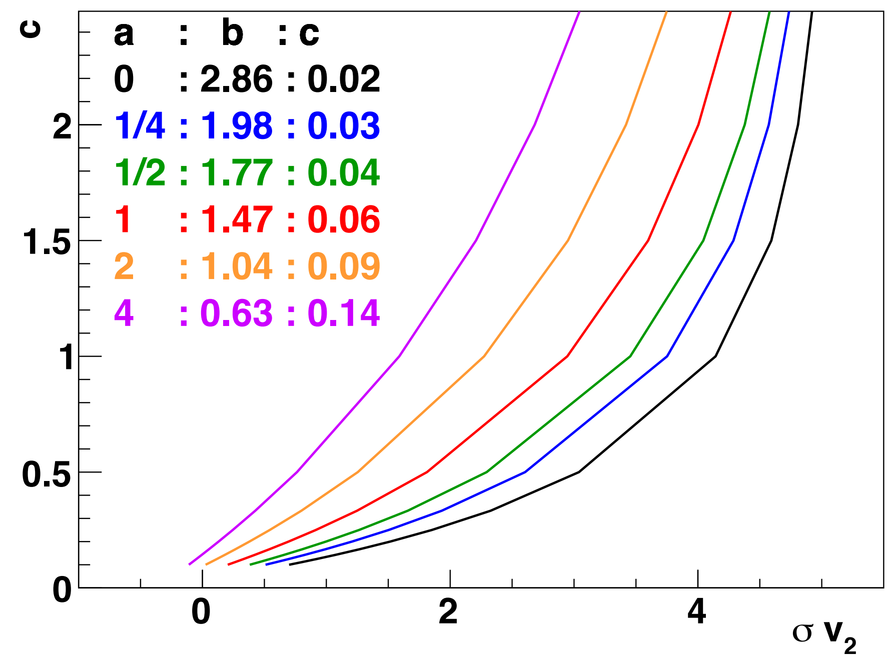
The time dependence of velocity is modified.

The azimuthal anisotropy dependence



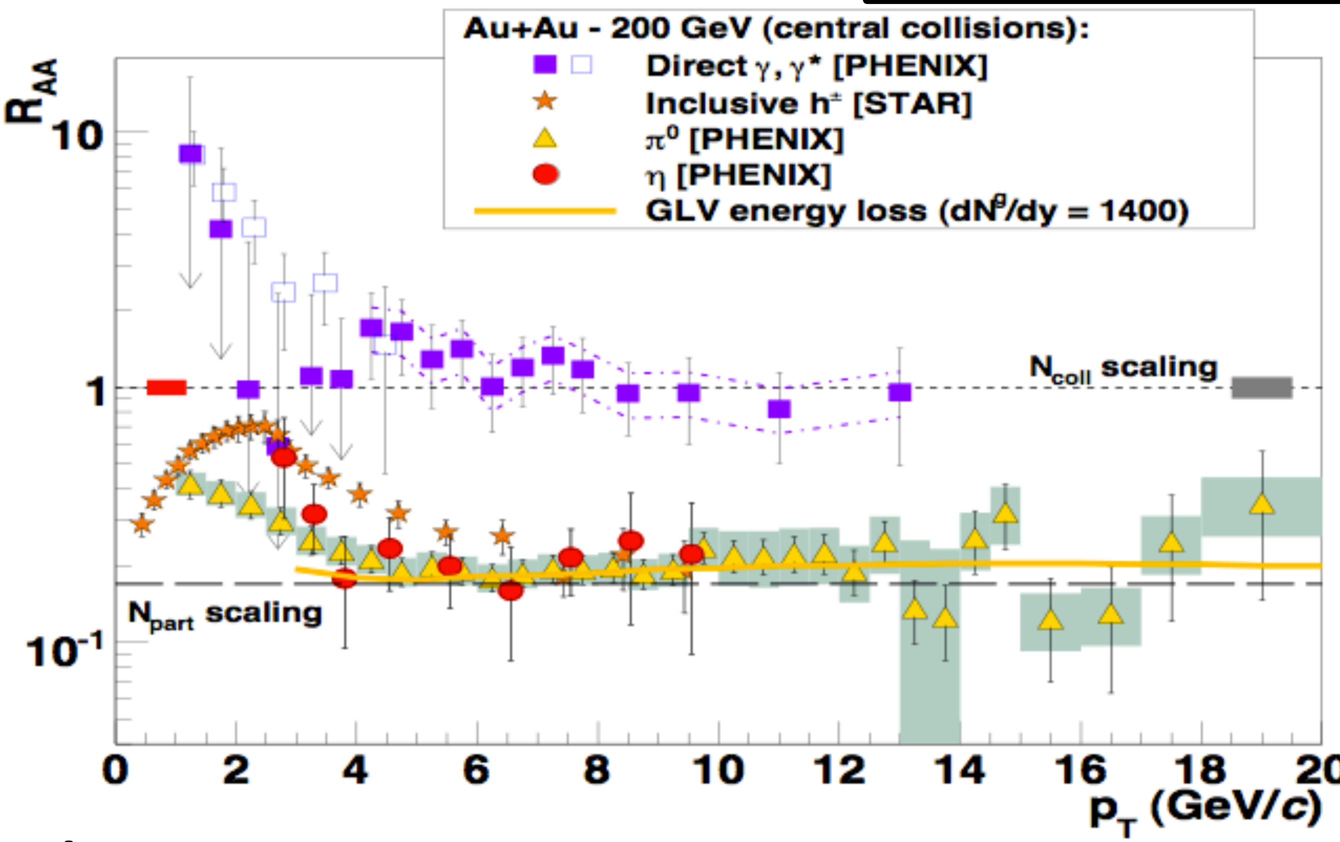
Selecting b and c





Medium effect (R_{AA})

$$R_{AA} = \frac{(1/N^{evt}_{AA}) d^2 N_{AA}/dp_T dy}{< N_{coll} > /\sigma^{inel}_{pp} \times d^2\sigma_{pp}/dp_T dy}$$



R_{AA}=1
not modified

R_{AA}≠1
medium effect

Hadron
less than unity
-> medium effect

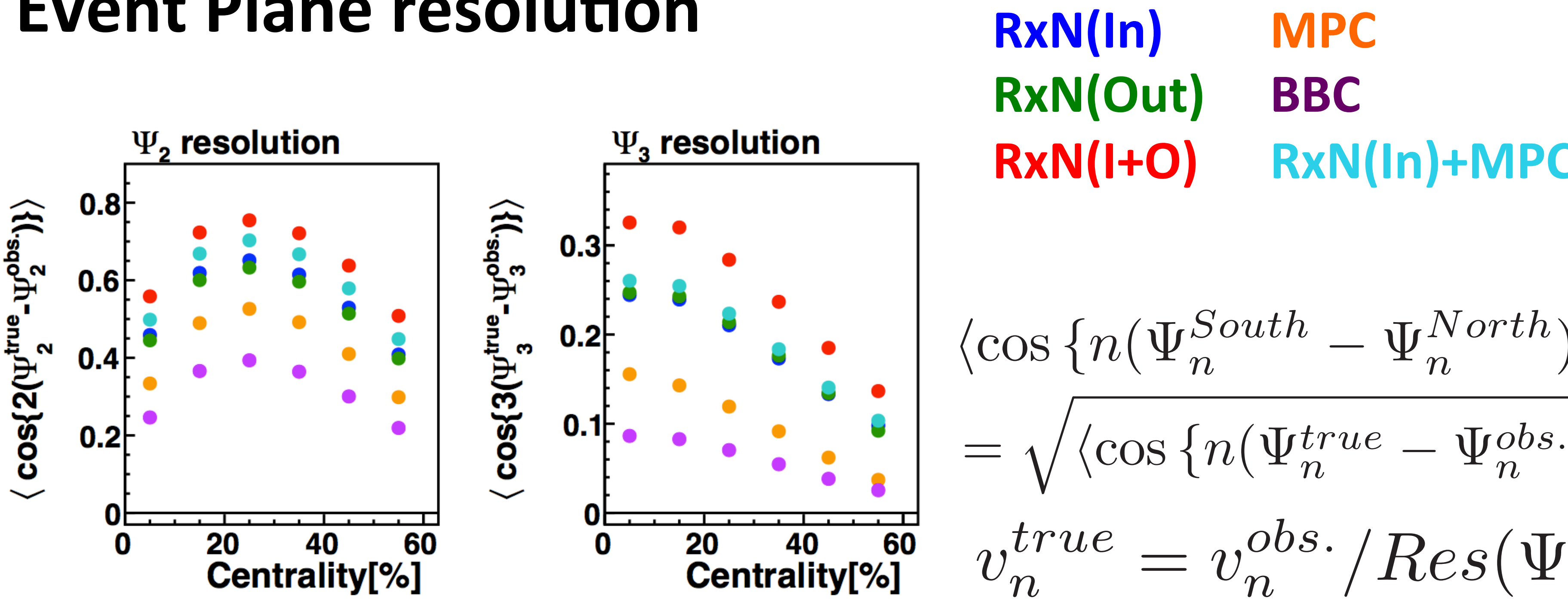
photon

R_{AA}=1 : not modified

-> Emitted from initial hard scattering

R_{AA}>>1 : There are other photon sources which are not in p+p collisions.

Event Plane resolution

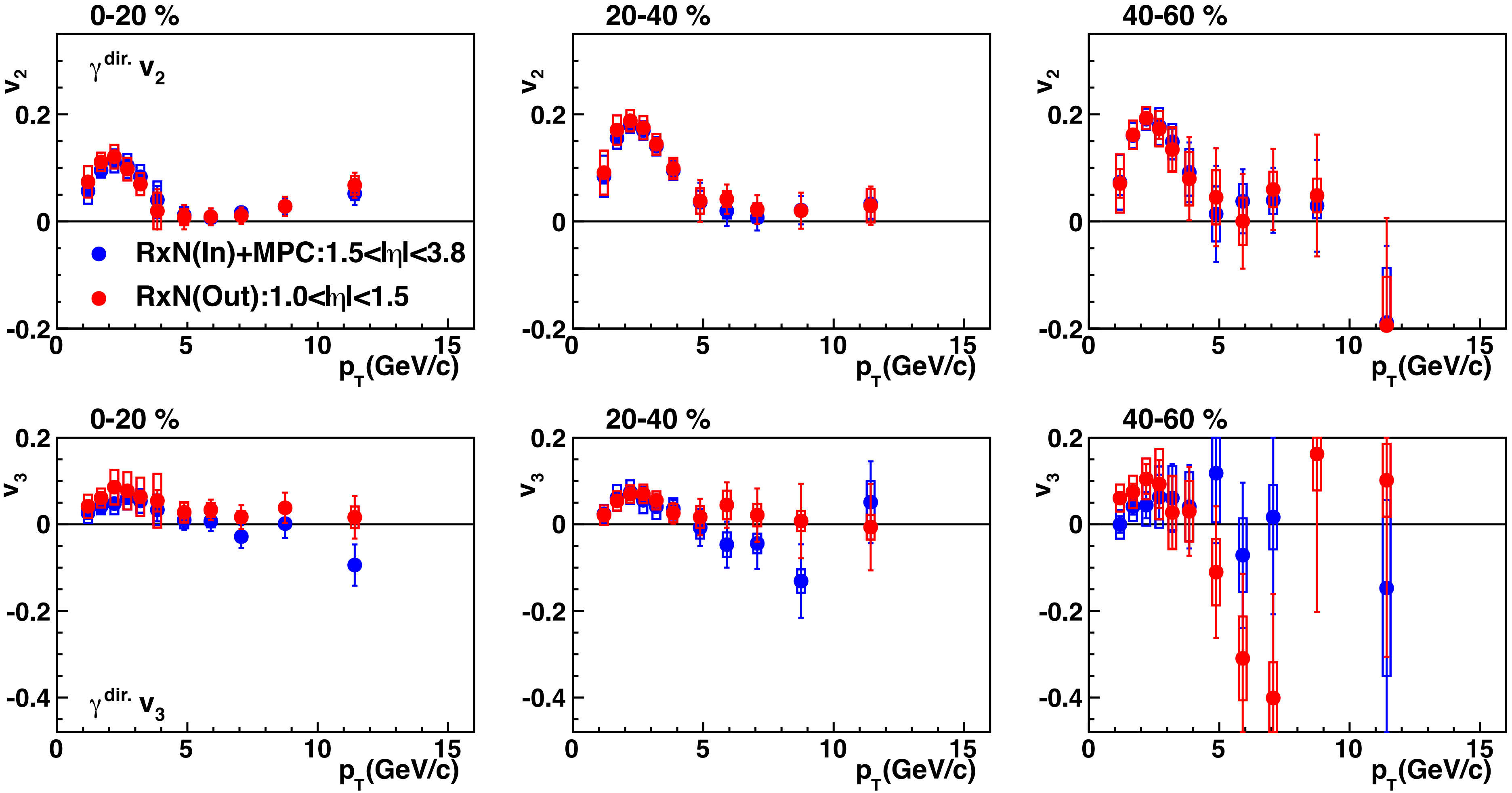


$$\langle\cos\{n(\Psi_n^{South}-\Psi_n^{North})\}\rangle$$
$$=\sqrt{\langle\cos\{n(\Psi_n^{true}-\Psi_n^{obs.})\}\rangle}$$
$$v_n^{true}=v_n^{obs.}/Res(\Psi_n)$$

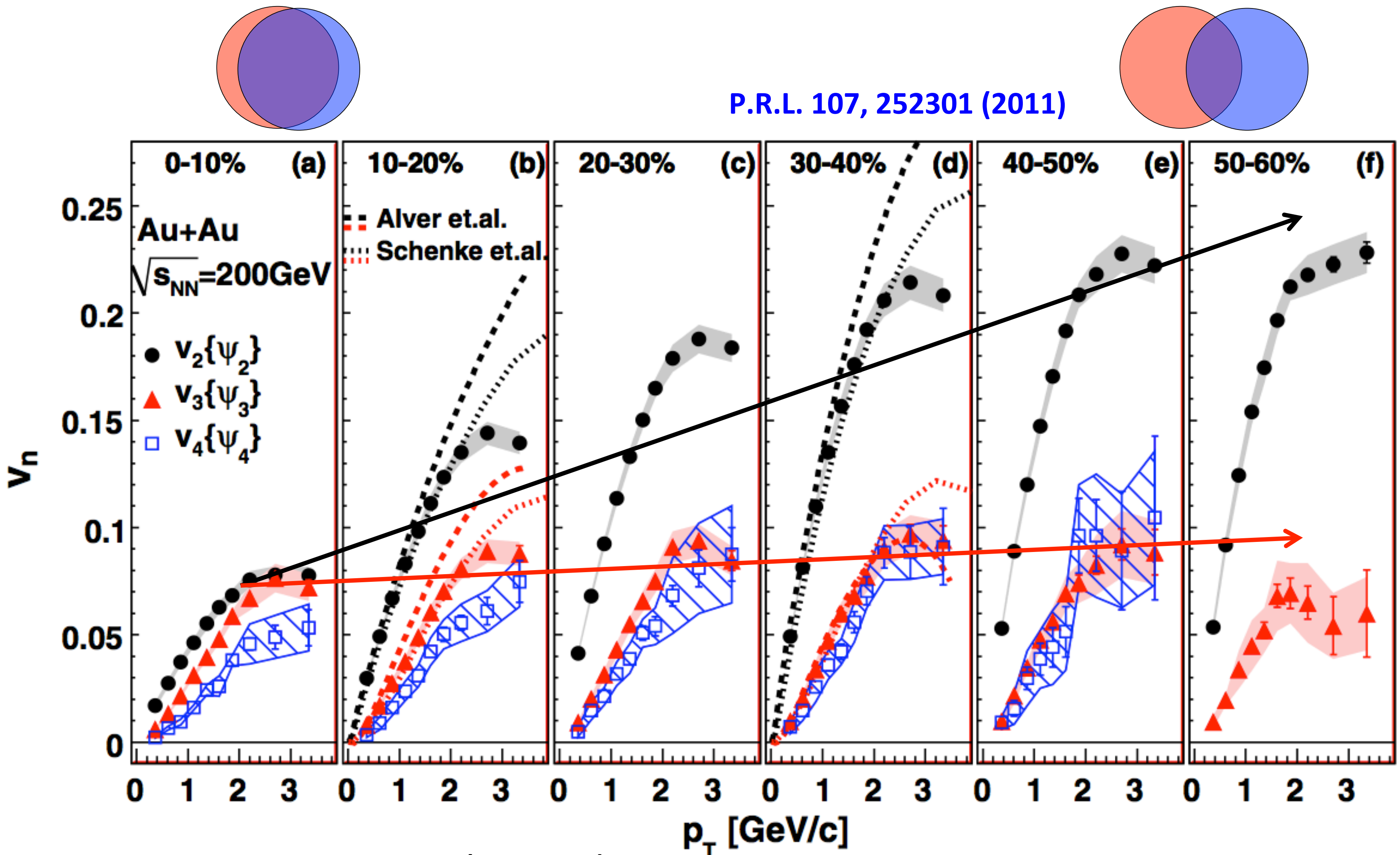
Extracted from the correlation between the event plane angle measured by south and north.

The v_n measured with event plane should be corrected by the resolution.

The event plane dependence of direct photon v_n



Charged hadron v_n

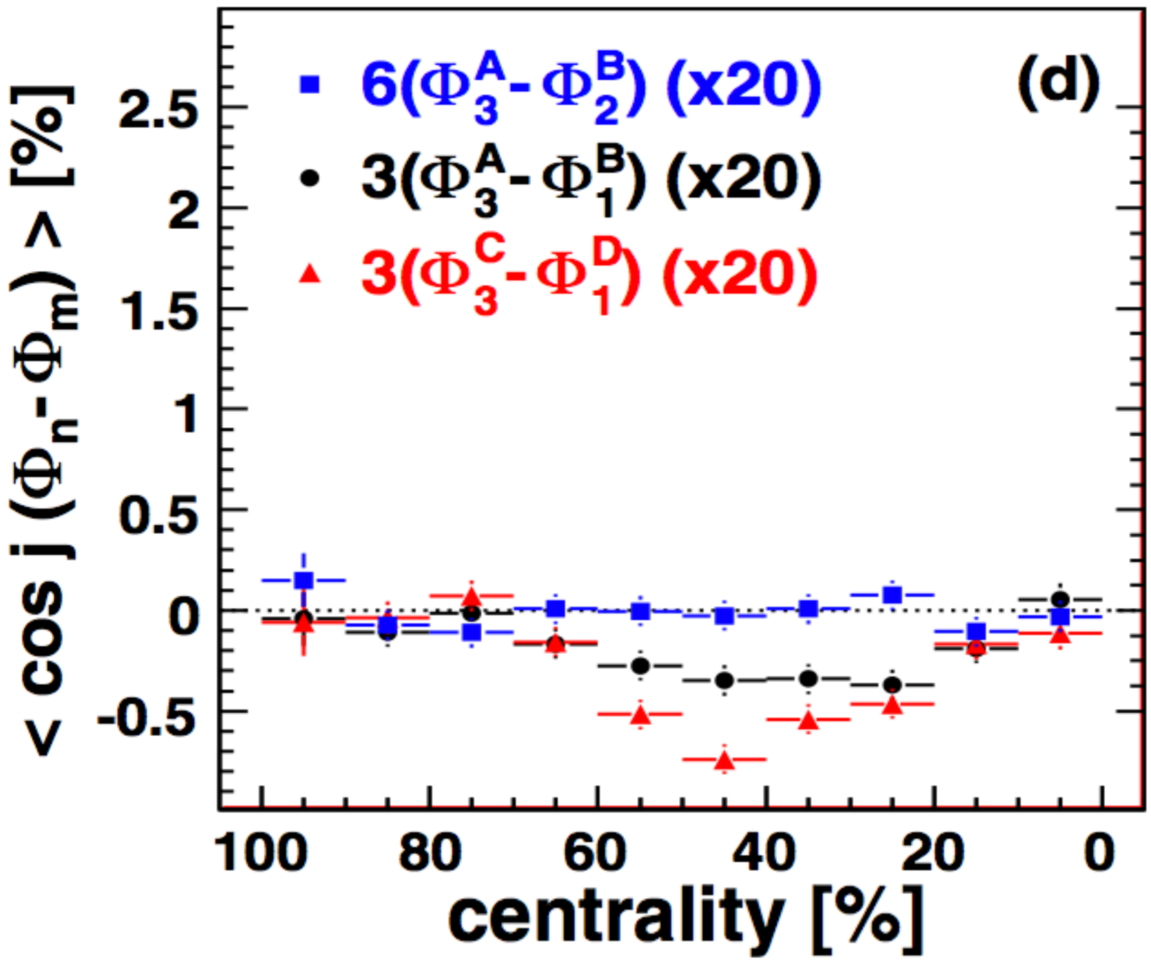


Non-zero positive v_n are observed.

The trend of centrality dependence is not similar.

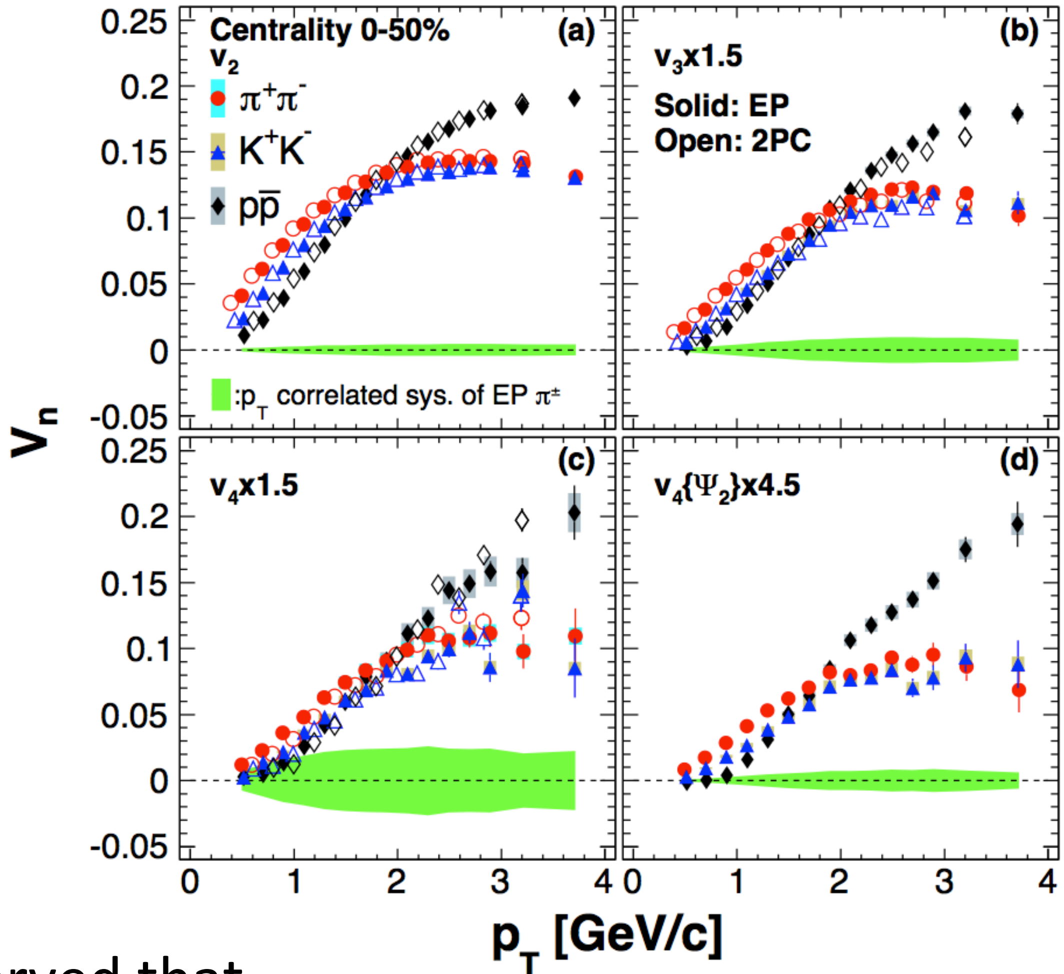
Event Plane correlation

P.R.L. 107, 252301 (2011)



Ψ_2 and Ψ_3 are uncorrelated.

Identified charged particle v_n



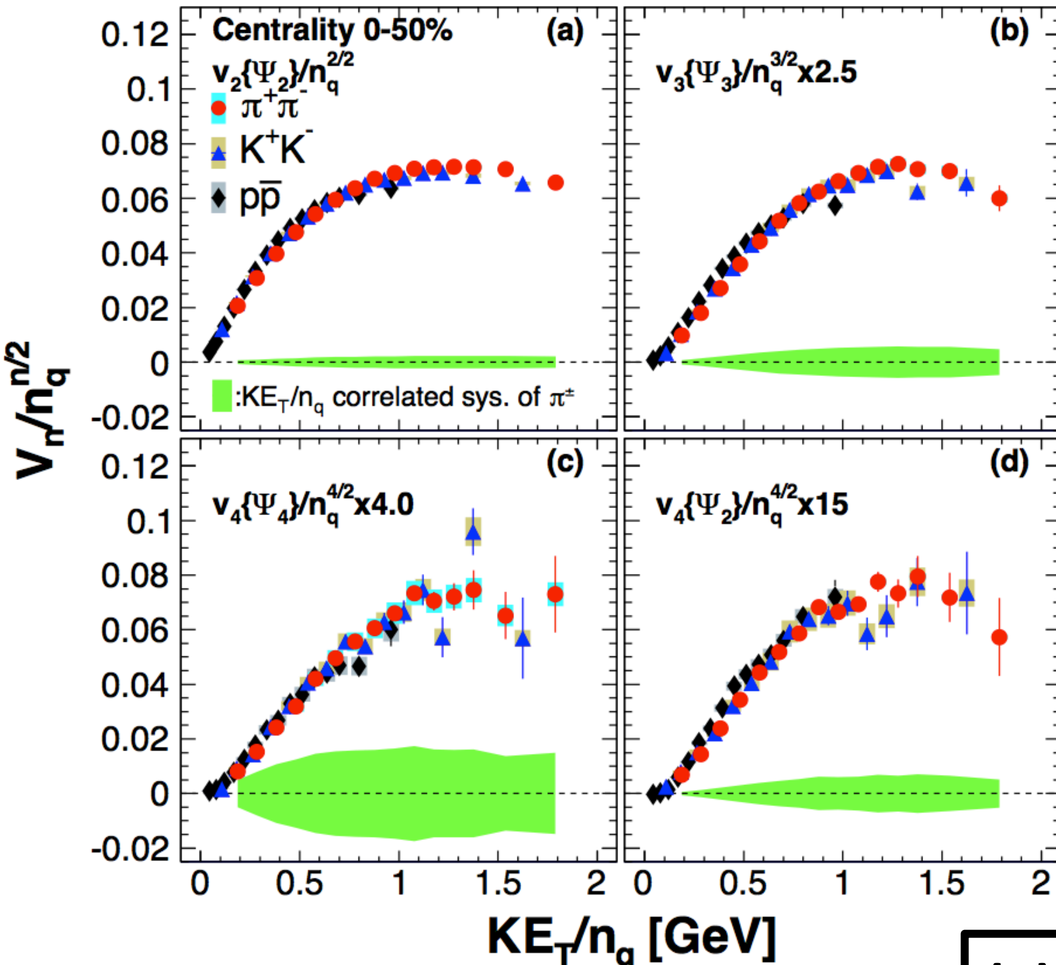
arXiv:1412:1038

It is observed that

all harmonics have mass ordering

there are meson and baryon splitting

The number of constituent quark scaling (NCQ scale)



arXiv:1412:1038

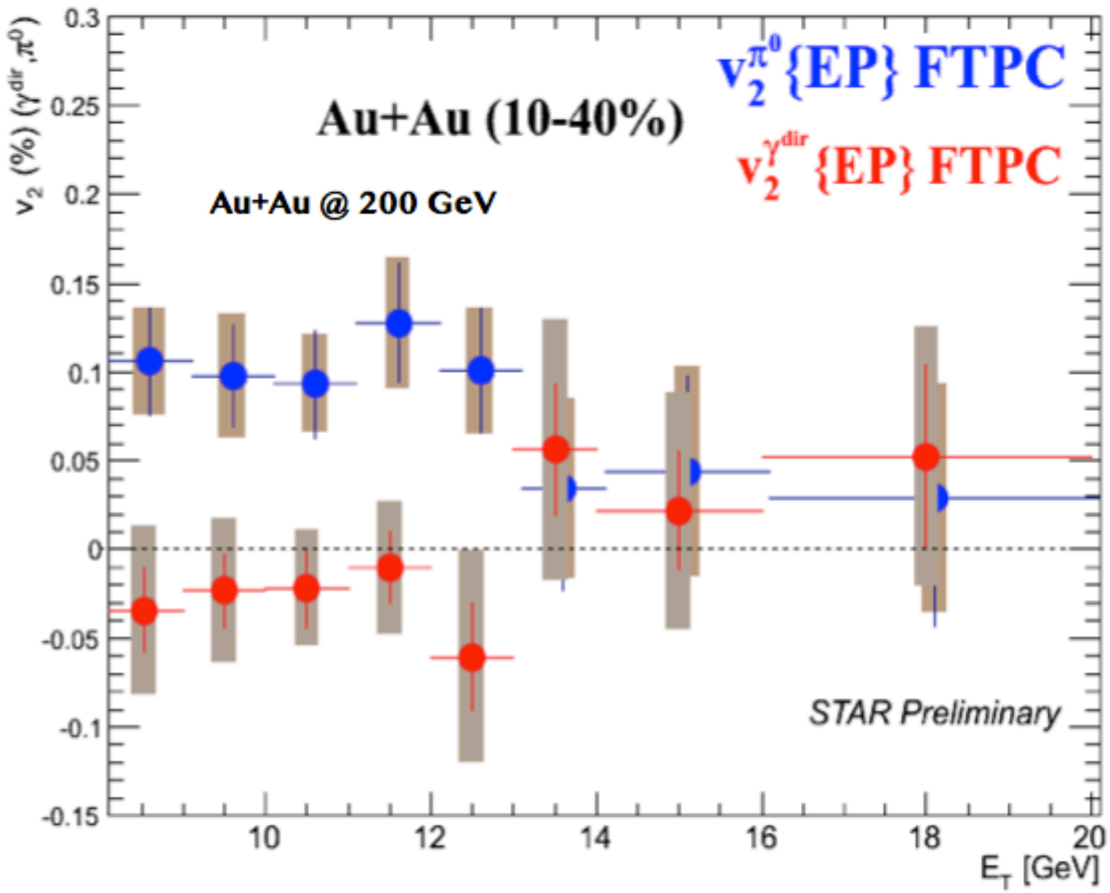
All particles are scaled by modified NCQ scaling.

(a) : $v_2(KE_T)/n_q$
(b) : $v_n^{1/n}$ scaling
(a)+(b) : $v_n(KE_T)/n_q^{n/2}$

π^0 and $\gamma^{dir.}$ v_2 measurement by STAR

Ahmed M. Hamed
shown at QM

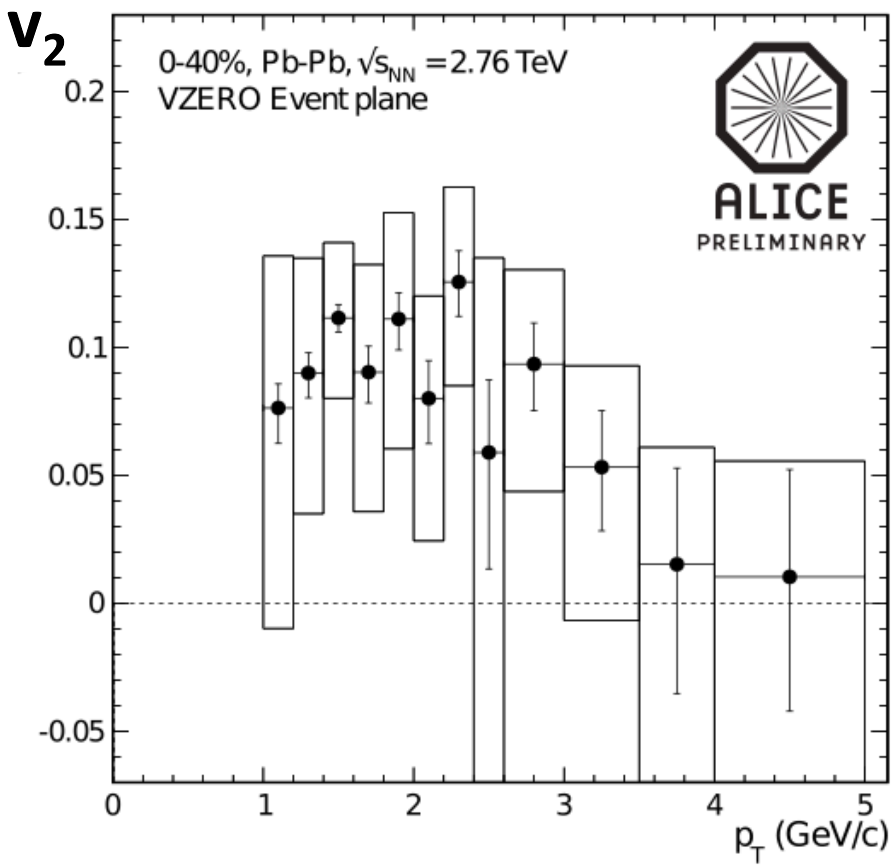
✓ BEMC: $|\eta| < 1.0$, FTPC: $2.5 < |\eta| < 4.0$



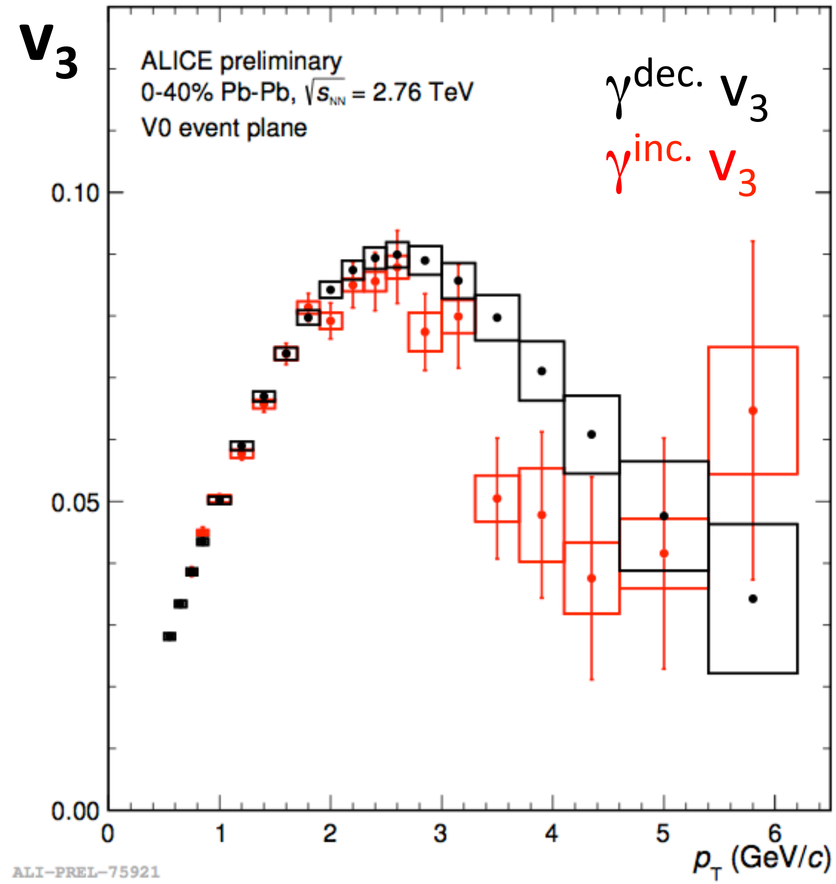
$\gamma^{dir.}$ v_2 in high E_T region are consistent with 0 within systematic uncertainty, while π^0 has positive v_2.

photon v_n measurement by ALICE

arXiv:1212.3995v2

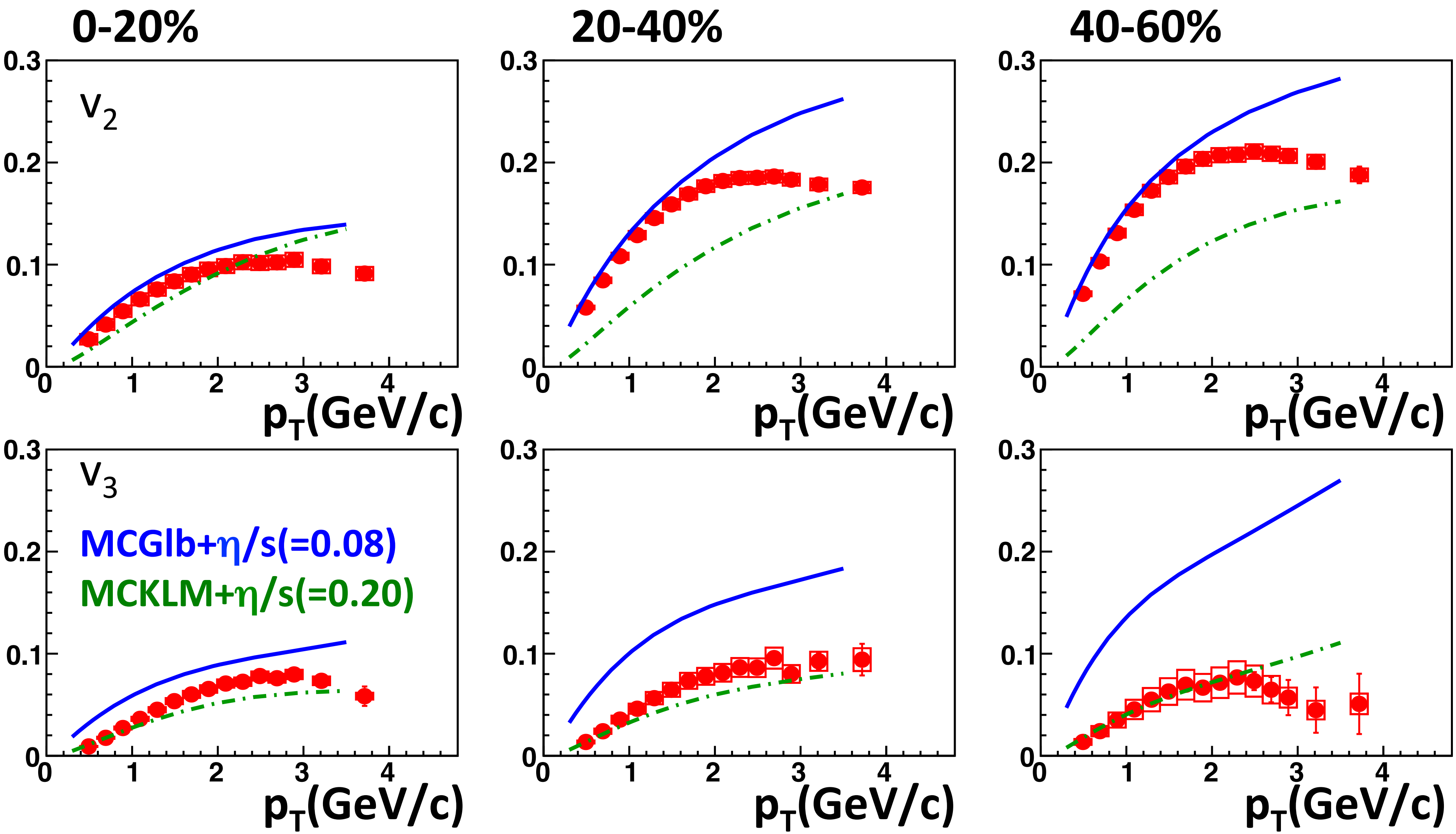


Friederike shown at QM



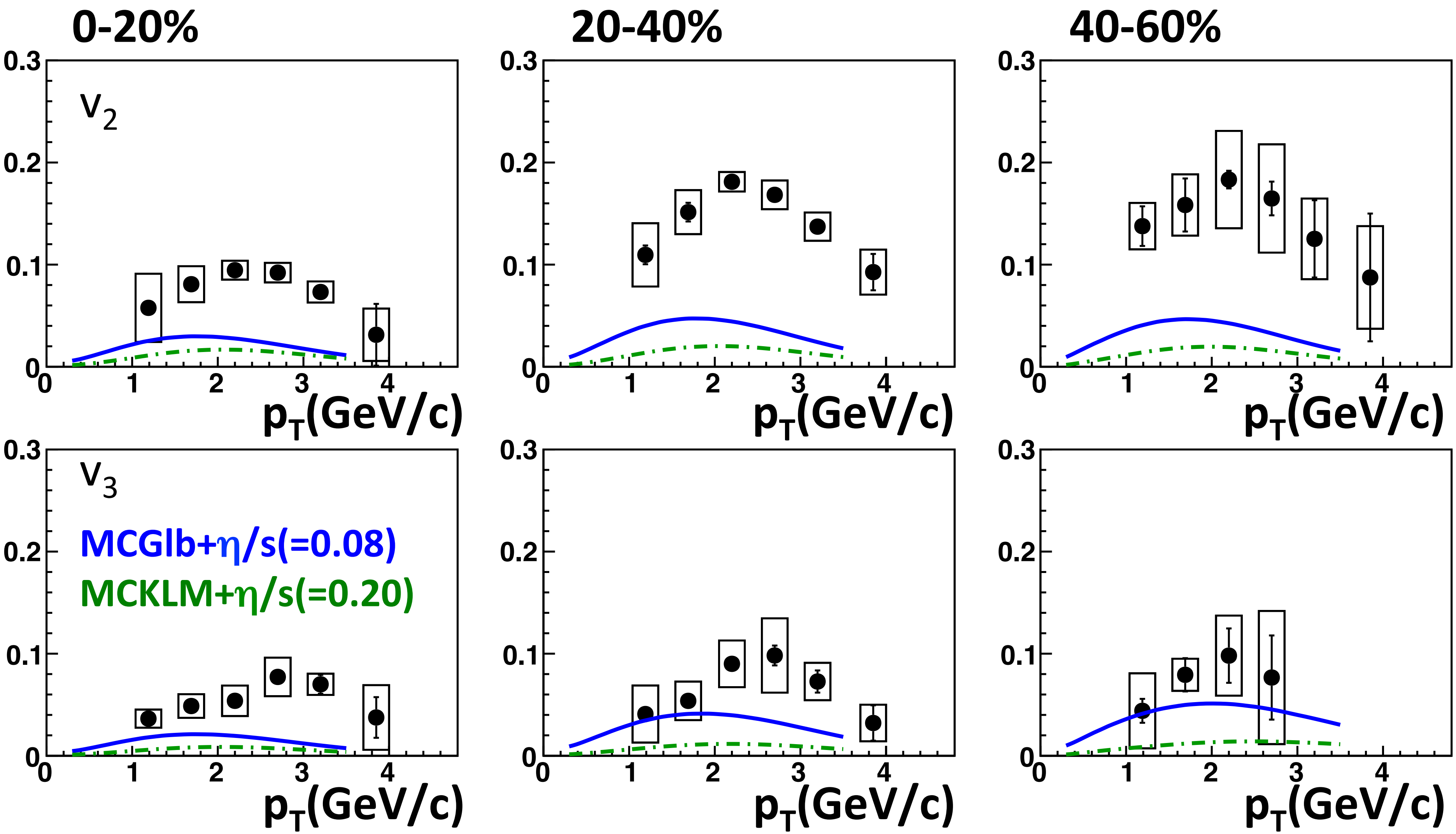
It is also observed that $\gamma^{dir.}$ v_2 is positive in low p_T at LHC-ALICE.
v_3 measurement is ongoing.

The comparison of charged pion and hydro-model



$\pi^{\pm}$: arXiv:1412:1038
Model : arXiv:1403.7558
Private communication

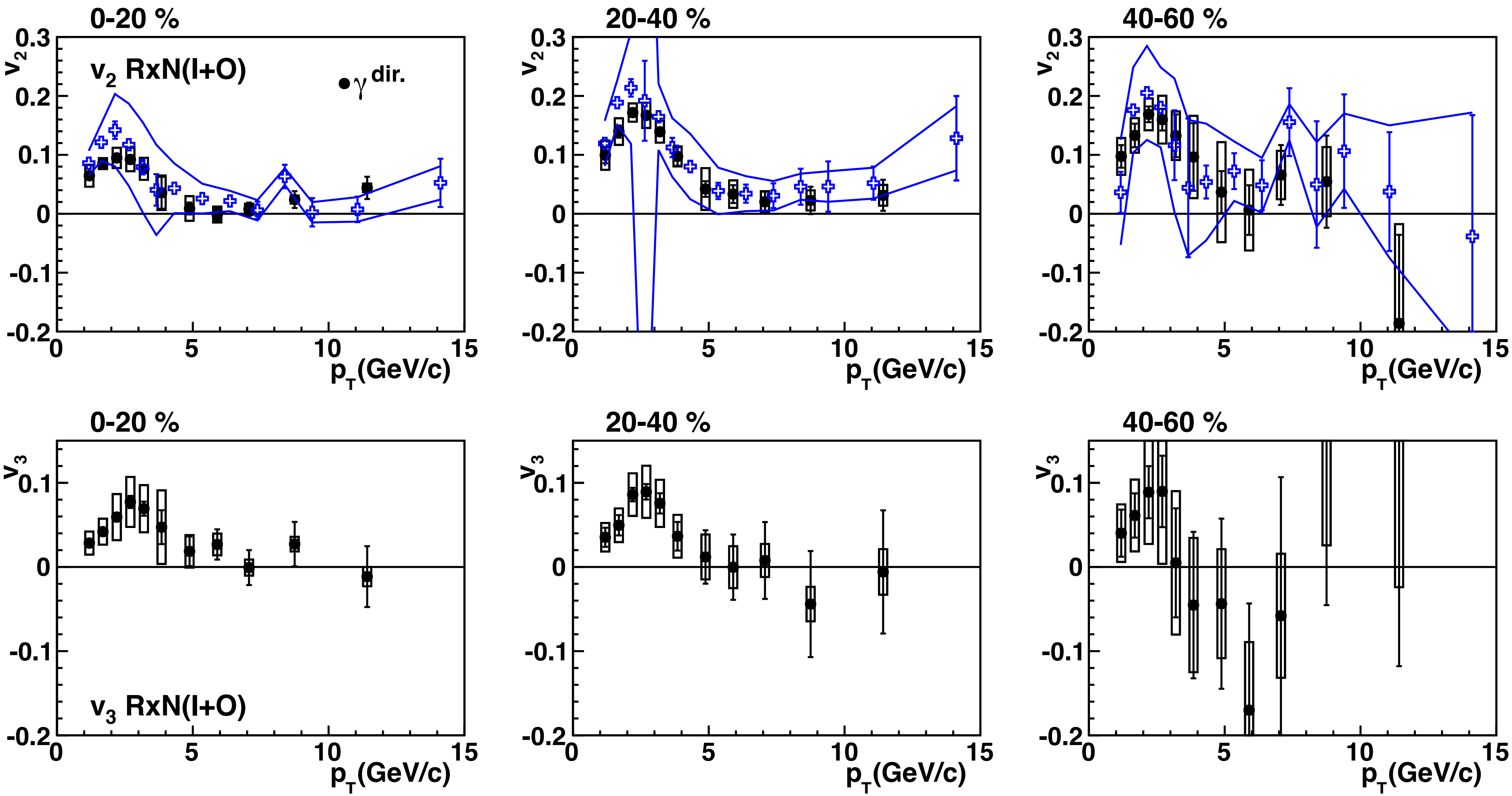
The comparison of direct photon and hydro-model



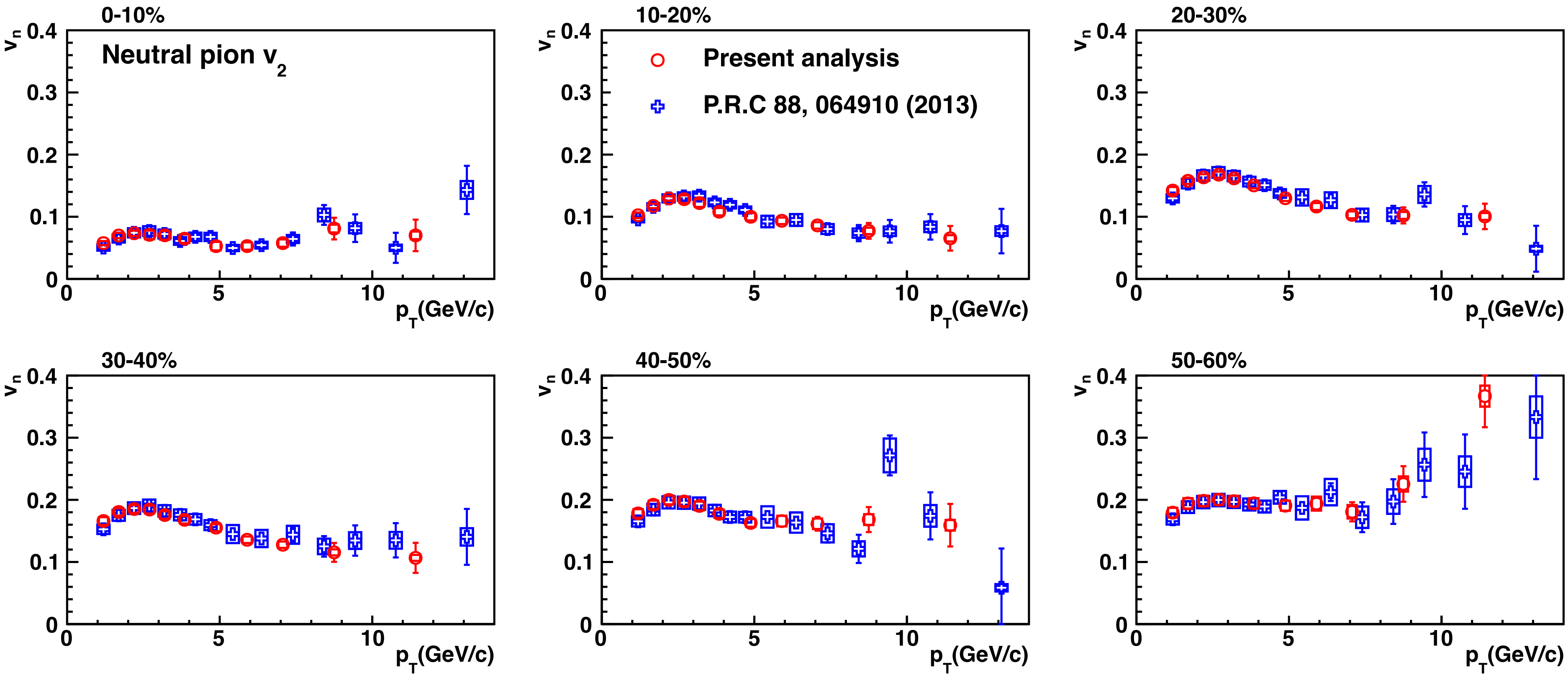
$\pi^{\pm}$: arXiv:1412:1038

Model : arXiv:1403.7558

Private communication

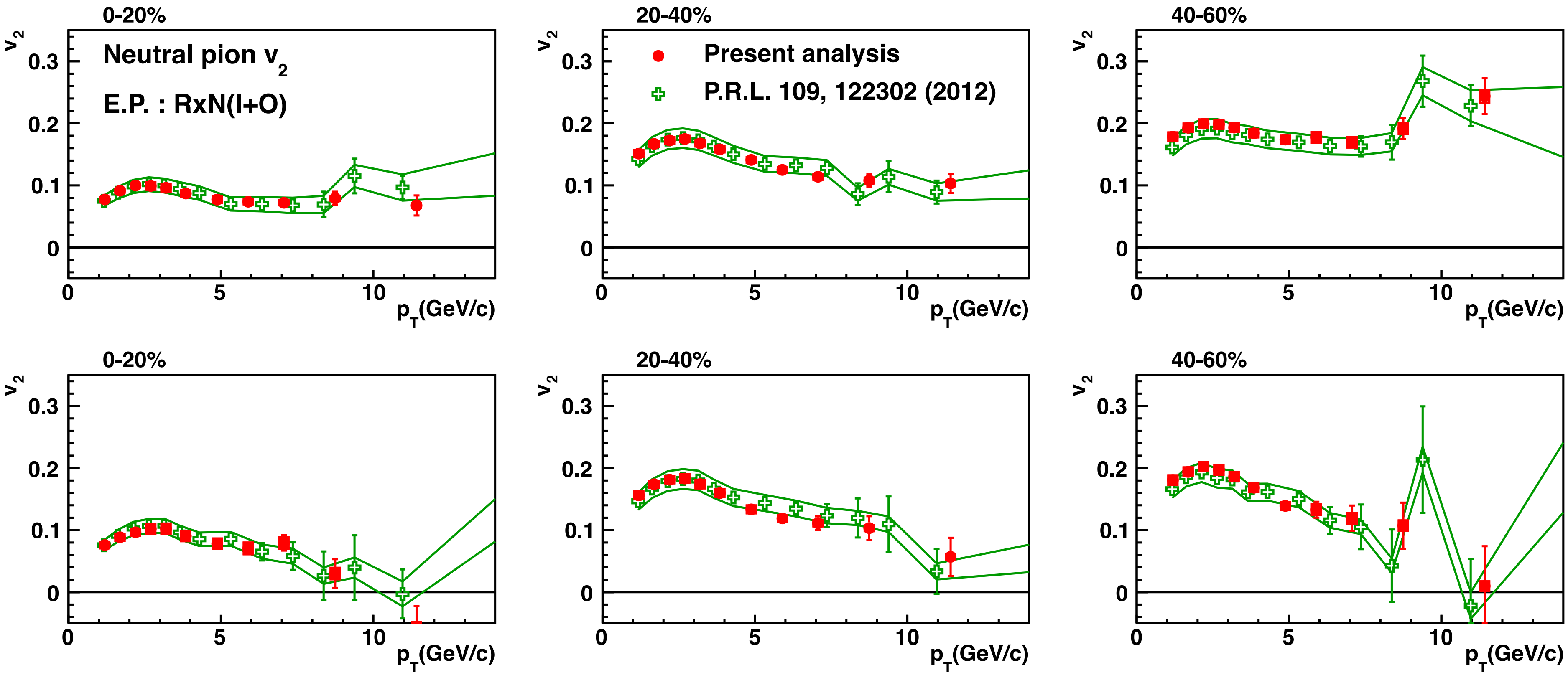

0-20 %
20-40 %
40-60 %
v_2 RxN(I+O)
$\gamma^{dir.}$
v_3 RxN(I+O)
v_2
v_3
p_T(GeV/c)

Comparison of neutral pion v_2 with previous results



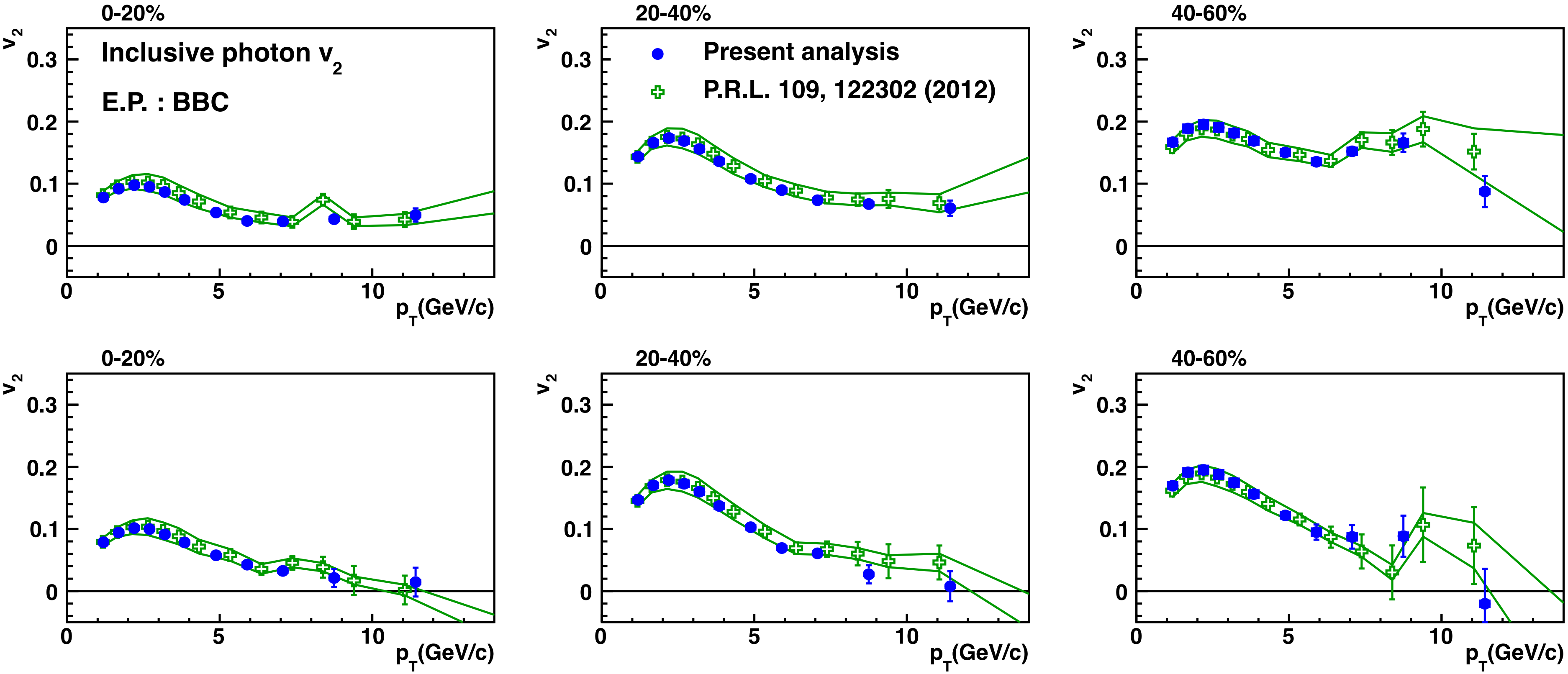
They are consistent within systematic uncertainty.

Comparison of neutral pion v_2 with previous results



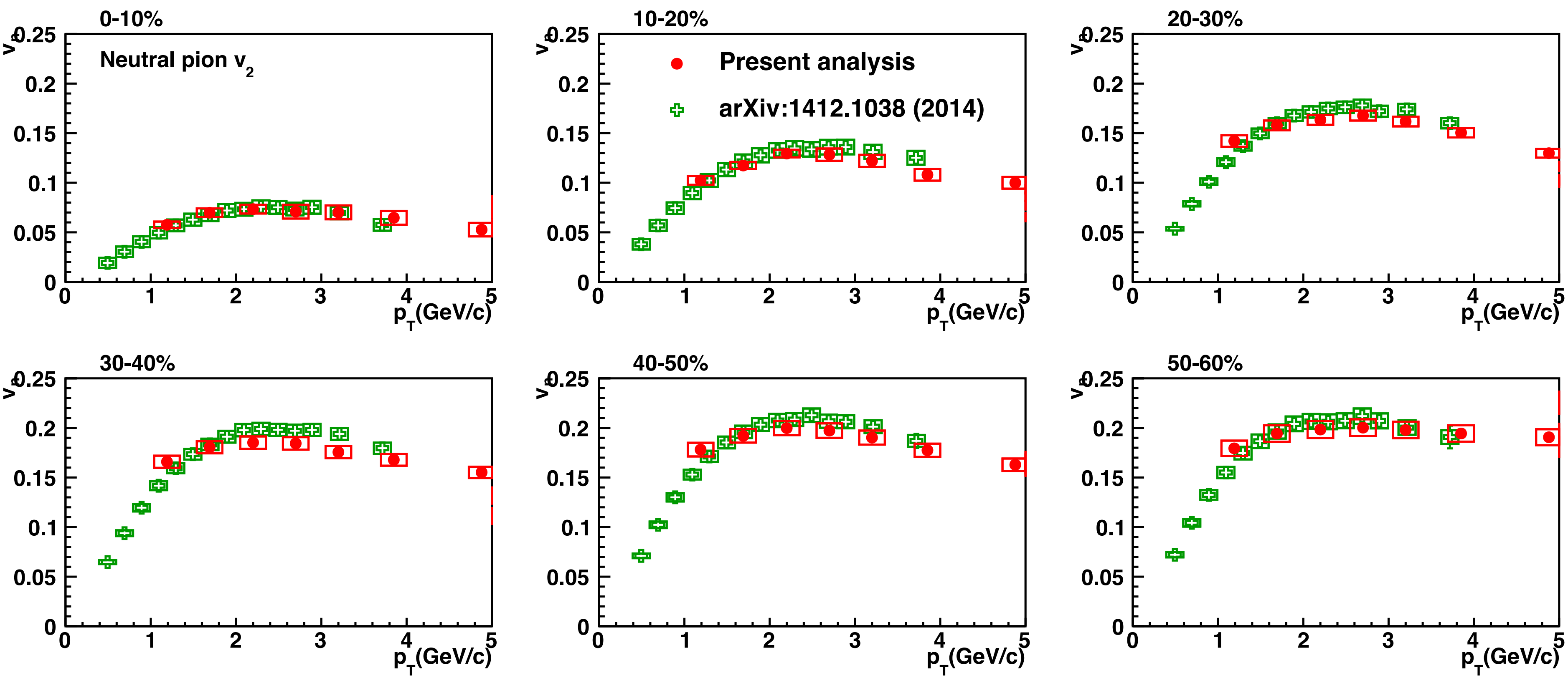
They are consistent within systematic uncertainty.

Comparison of inclusive photon v_2 with previous results



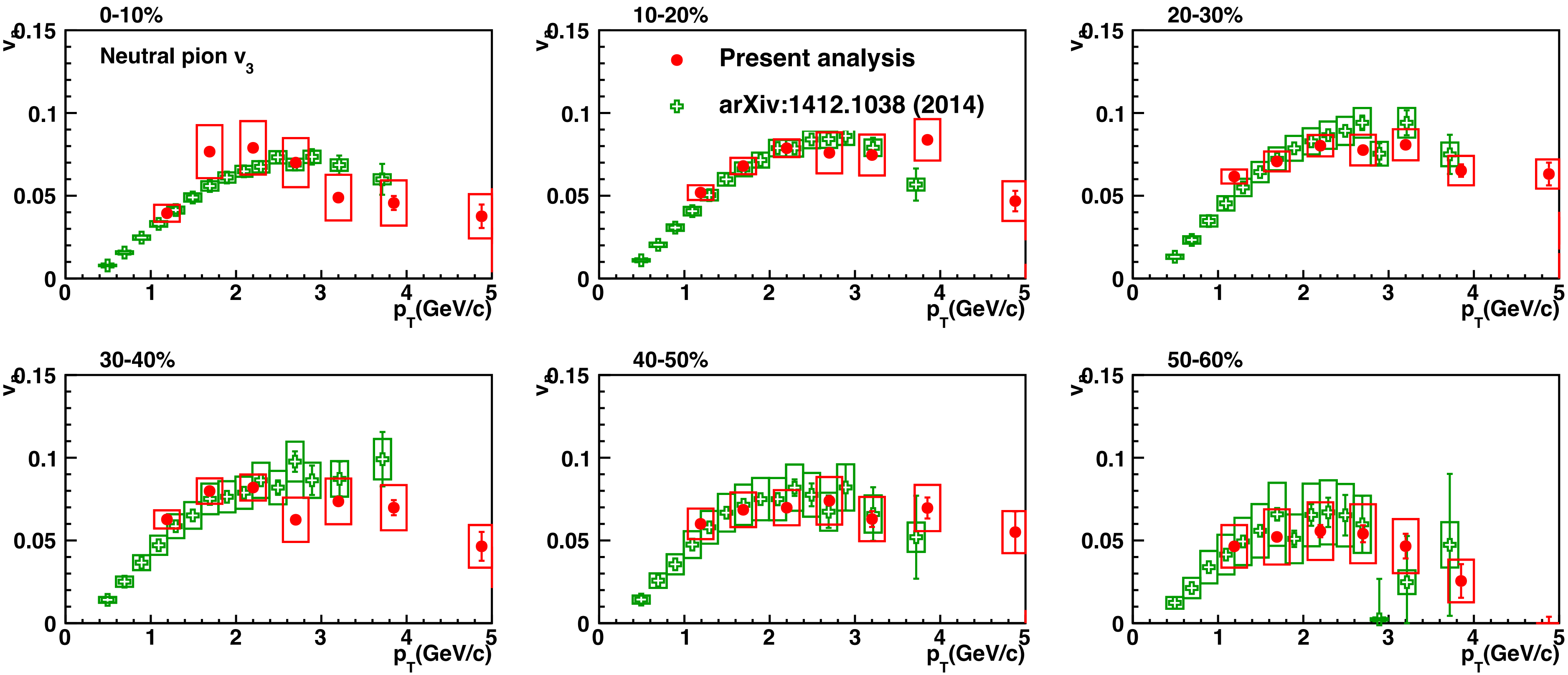
They are consistent within systematic uncertainty.

Comparison of neutral pion v_2 with charged pion v_2



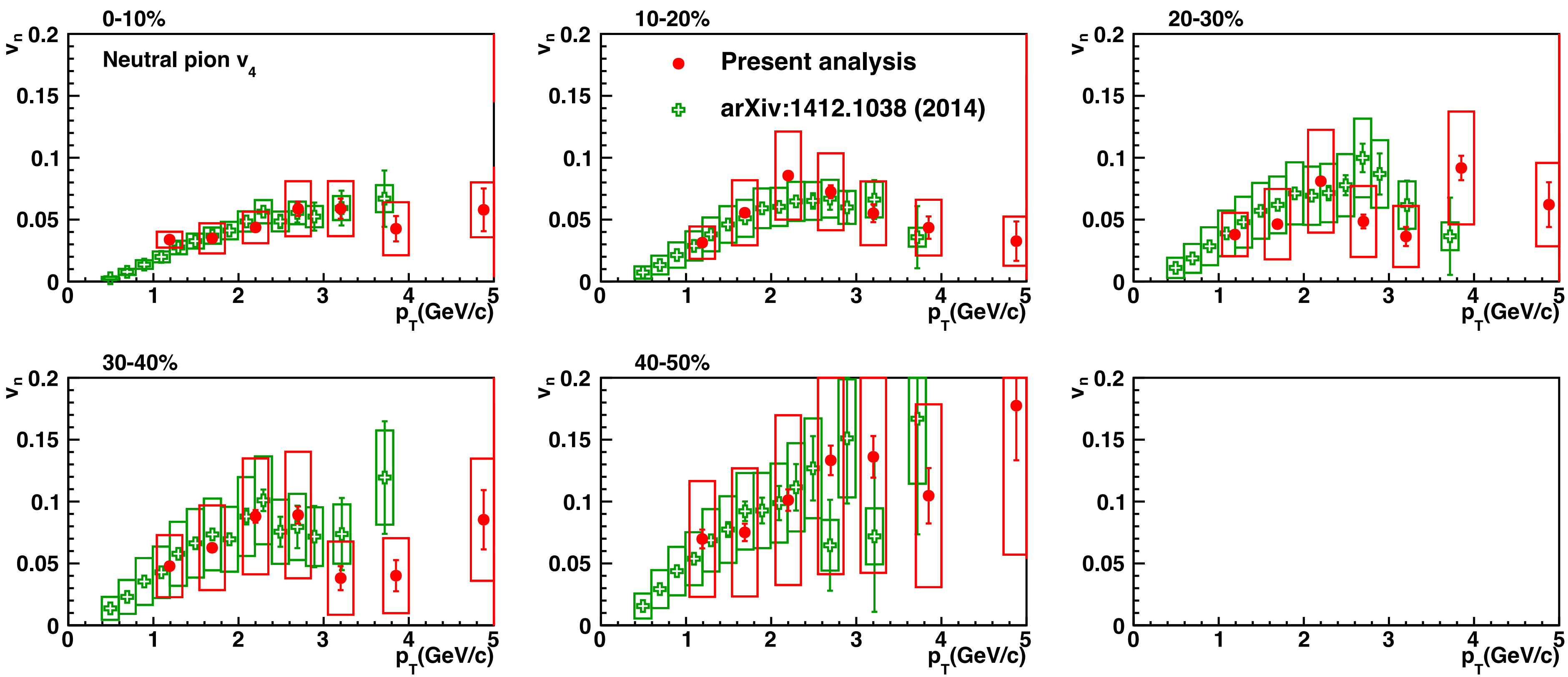
They are consistent within systematic uncertainty.

Comparison of neutral pion v_3 with charged pion v_3



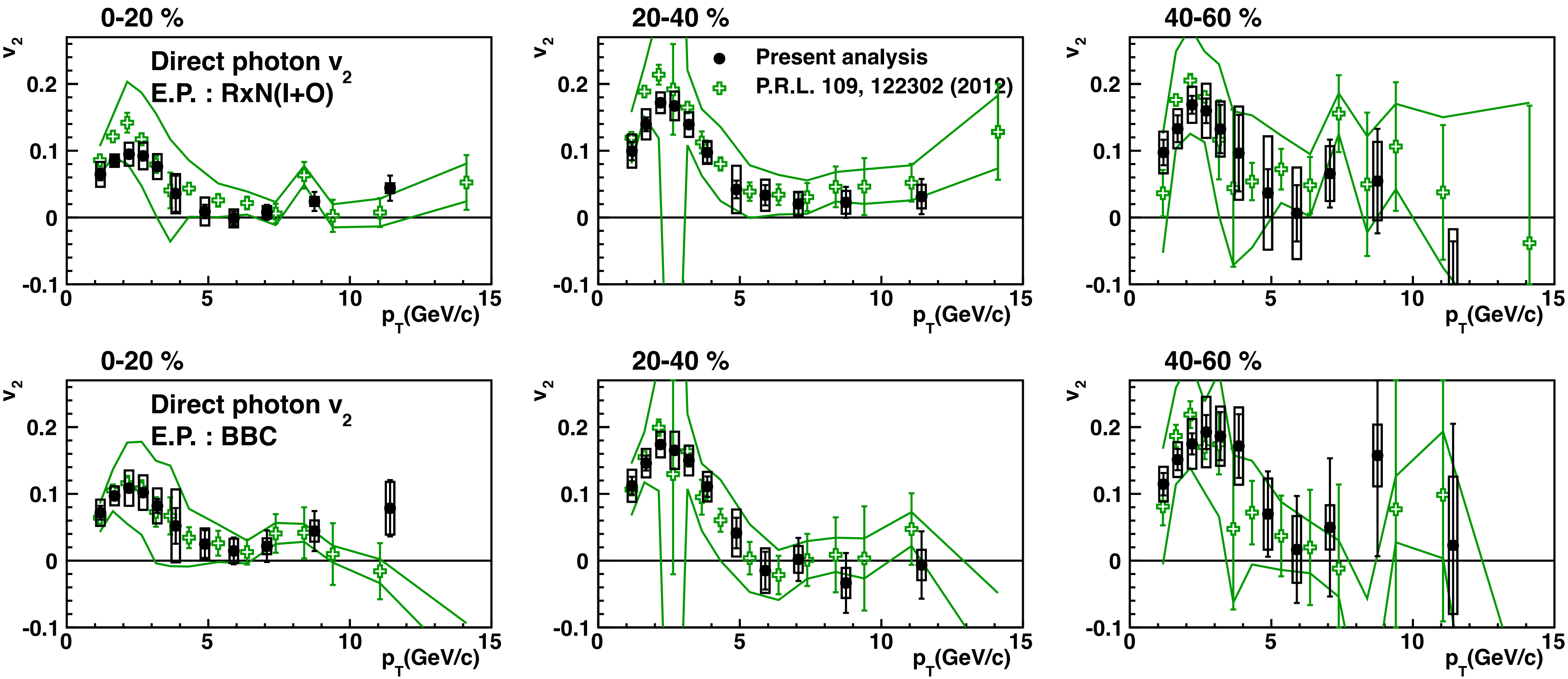
They are consistent within systematic uncertainty.

Comparison of neutral pion v_3 with charged pion v_3



They are consistent within systematic uncertainty.

Comparison of direct photon v_2 with previous results



They are consistent within systematic uncertainty.